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Comparisons of Motions for HMCS NIPIGON with Numerical Predictions

Kevin A. McTaggart and David Stredulinsky

Defence R&D Canada

External Client Report
DREA ECR 2001-156
October 2001

National Defence Défense nationale

Canada

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Defence Research Establishment Atlantic

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Abstract

This report presents comparisons between measured and predicted motions in waves for HMCS NIPIGON. The main objective of the study was to validate roll motion predictions; thus, trial runs selected for the present study are limited to bow quartering, beam, and stern quartering seas. Significant wave heights are between 3 and 6 m, and all wave spectra have a dominant direction. Motion predictions from the time domain code FREDYN and the frequency domain codes SHIPMO7 and PRECAL are presented. FREDYN can only predict motions in long-crested seas; however, the ratio of SHIPMO7 predictions for short and long-crested seas provides a means for estimating motions from FREDYN in short-crested seas. All three programs give good agreement with measured heave and pitch motions. For roll motions, SHIPMO7 gives good agreement while FREDYN gives fair agreement. The poor agreement of PRECAL roll predictions is likely due to the accidental absence of bilge keel damping in Version 4 of the code.

Résumé

Ce rapport compare les mouvements prévus et observés du NCSM Nipigon dans la houle. Puisque cette étude avait comme objectif principal de valider les prévisions du roulis, nous avons limité nos essais en mer à des houles trois-quarts avant, de travers et trois-quarts arrière. Les lames significatives avaient une amplitude entre 3 et 6 m et tous les spectres des lames présentaient une direction dominante. Nous présentons les mouvements prévus par le logiciel FREDYN qui fait les calculs dans le domaine temporel et par les logiciels SHIPMO7 et PRECAL qui calculent dans le domaine des fréquences. FREDYN ne prédit les mouvements que pour les houles longues. Toutefois, on peut utiliser le quotient des prévisions de SHIPMO7 pour les houles courtes et longues pour estimer, à partir des résultats de FREDYN, les mouvements de navires soumis à une houle courte. L'accord entre les prévisions des trois programmes et les mouvements de soulèvement et de tangage est bon. Pour le roulis, les résultats de SHIPMO7 concordent bien avec les observations, tandis que ceux de FREDYN concordent assez bien. L'omission fortuite, dans la quatrième version du logiciel PRECAL, des effets d'amortissement par la quille de roulis pourrait expliquer l'écart entre les prévisions et les observations du roulis.

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Executive summary

Introduction

This report compares motion predictions in waves with measured motions from a sea trial on HMCS NIPIGON. The primary goal is to validate roll motion predictions from SHIPMO7, PRECAL, and FREDYN. The trial runs selected for this study have dominant relative sea directions of bow quartering, beam, or stern quartering.

Principal Results

FREDYN can only predict motions in long-crested seas; however, the ratio of SHIPMO7 predictions for short and long-crested seas provide a means for estimating motions from FREDYN in short-crested seas. All three programs give good agreement with measured heave and pitch motions. For roll motions, SHIPMO7 gives good agreement while FREDYN gives fair agreement. The poor agreement of PRECAL roll predictions is likely due to the accidental absence of bilge keel damping in Version 4 of the code.

Significance of Results

SHIPMO7 is the only numerical code that gives consistently good roll predictions for the trial conditions. While all three codes have a similar theoretical basis for predicting roll damping, the differences in results suggest different implementations. The PRECAL implementation is missing bilge keel damping, and possibly has other errors. The FREDYN implementation likely gives lower roll damping values than SHIPMO7, and is a possible area for improvement.

Future Plans

The next version of PRECAL will include bilge keel damping forces. The results from the present study will be forwarded to the Cooperative Research Ships PRECAL Working Group and the Cooperative Research Navies Dynamic Stability Project to assist with improvements to numerical predictions. The good predictions from SHIPMO7 indicate that extension of the code to include 3 dimensional hydrodynamic coefficients could be worthwhile.

Kevin A. McTaggart and David Stredulinsky; 2001; Comparisons of Motions for HMCS NIPIGON with Numerical Predictions; DREA ECR 2001-156; Defence Research Establishment Atlantic.

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Sommaire

Introduction

Dans ce rapport nous comparons les mouvements prévus dans la houle aux mouvements mesurés lors d'un essai en mer avec le NCSM Nipigon. L'objectif principal était de valider les prévisions du roulis par les logiciels SHIPMO7, PRECAL et FREDYN. Nous avons choisi pour cette étude des essais pendant lesquels la direction dominante de la houle était trois-quarts avant, de travers et trois-quarts arrière.

Résultats principaux

FREDYN ne prédit les mouvements que pour les houles longues. Toutefois, on peut utiliser le quotient des prévisions de SHIPMO7 pour les houles courtes et longues pour estimer, à partir des résultats de FREDYN, les mouvements des navires dans une houle courte. Les prévisions des trois programmes concordent bien avec les mouvements de soulèvement et de tangage. Pour le roulis, les résultats de SHIPMO7 concordent bien avec les observations, tandis que ceux de FREDYN concordent assez bien. L'omission fortuite, dans la quatrième version du logiciel PRECAL, des effets d'amortissement par la quille de roulis pourrait expliquer l'écart entre les prévisions et les observations du roulis.

Importance des résultats

Le logiciel SHIPMO7 est le seul qui donne invariablement de bonnes prévisions du roulis lors des essais. Bien que les trois logiciels reposent sur une base théorique similaire pour la prévision de l'amortissement du roulis, les différences de leurs résultats permettent de penser que cette base est appliquée différemment. Le logiciel PRECAL ne tient pas compte de l'amortissement de la quille de roulis et c'est possible qu'il comporte d'autres erreurs. Le logiciel FREDYN donne probablement, pour l'amortissement du roulis, des valeurs plus faibles que celles obtenues avec le logiciel SHIPMO7, ce qui constitue un domaine où il est possible d'améliorer ce logiciel.

Travaux ultérieurs prévus

La prochaine version de PRECAL inclura les forces d'amortissement de la quille de roulis. Les résultats de cette étude seront acheminés au groupe de travail PRECAL du consortium des Co-operative Research Ships et aux responsables du projet sur la stabilité dynamique du consortium des Cooperative Research Navies et contribueront à améliorer les prévisions par ordinateur. Les bonnes prévisions faites par SHIPMO7 nous portent à croire qu'il serait utile d'inclure, dans les améliorations du logiciel, des coefficients d'hydrodynamique tridimensionnelle.

Kevin A. McTaggart and David Stredulinsky; 2001; Comparaisons Entre les Mouvements Prévus et Observés du NCSM Nipigon; DREA ECR 2001-156; Centre de Recherches pour la Défense Atlantique.

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1 Introduction

Ship motion predictions are commonly used to assist with safe design and operation of naval ships. Validation of ship motion codes is an essential element of their development. Model tests are the most common source of validation data for ship motion codes; however, experimental results will be influenced by scale effects. Among ship motion modes, roll will likely be most affected by scale effects due to the relative importance of viscous forces on roll damping. Consequently, ship motion predictions should ideally be validated with results from full-scale trials.

This report presents comparisons of numerical predictions with full-scale results from HMCS NIPIGON. The primary goal of the study is to evaluate roll predictions from the codes SHIPMO7, PRECAL 4.0, and FREDYN 8.2. Stredulinsky et al. [1] give a comprehensive description of the trial. Section 2 of this report gives a summary description of the trial. Numerical predictions of motions for the trial conditions are described in Section 3. Section 4 describes analysis of the ship motion predictions, and is followed by presentations of measured and predicted motions in Section 5. Section 6 discusses comparisons between observed and predicted motions. Final conclusions are presented in Section 7.

2 Trial Description

The sea trial was conducted in December 1997 aboard HMCS NIPIGON, the last steam-driven destroyer in the Canadian Fleet (no longer in service). Figure 1 gives a body plan for NIPIGON and Table 1 gives particulars. The ship departed Halifax, Nova Scotia on December 1, 1997. It was intended to transit to the Hibernia oil platform site some 400 miles southeast of Newfoundland. Problems with one of the ship boilers and heavy sea states prevented the vessel from reaching this location and trials were conducted approximately 100 miles south of Newfoundland. The ship spent December 6th and 7th in port in St John's, Newfoundland and returned to sea on December 8th. The trial ended on December 12th upon return to Halifax.

A series of 71 trial runs of 20 minute duration was undertaken at two nominal ship speeds in head, bow, beam, quartering and following seas. Data were collected in higher sea states (4,5 and 6) for three days over December 2, 3 and 4th and for four days at lower sea states (2 and 3) over December 8 to 11th. The 'low' ship speed was about 8 knots and 'high' ship speed was between 14 and 18 knots depending on what speed the ship could maintain in the given sea state. Speed was limited due to the loss of one of the two ship boilers on the first day of the trial.

Data were gathered from an array of 24 pressure transducers outfitted in the hull below the waterline, 15 single strain gauges and 4 rosette strain gauges, a wave

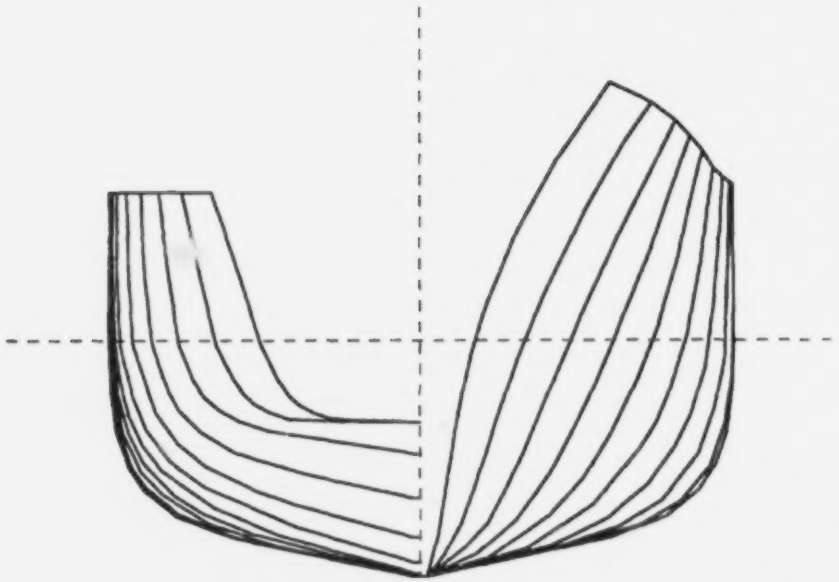

Figure 1: *Body Plan for HMCS NIPIGON*

Table 1: *Particulars for HMCS NIPIGON*

Displacement	3027 tonnes
Length between perpendiculars	108.4 m
Beam	12.8 m
Draft	4.3 m
Trim by stern	0.5 m
Height of CG above keel	5.1 m
CG from forward perpendicular	57.5 m
Block coefficient	0.503
Prismatic coefficient	0.625
Wetted hull area	1446 m^2
Metacentric height	1.2 m
Roll radius of gyration	5.6 m
Pitch radius of gyration	27.1 m

buoy, a TSK over-the-bow wave height meter, and the DREA ship motions package. Wave data were collected for 20 minutes out of every hour from the wave buoy. An Endeco type 1156 buoy was used for the first 3 days of the trial, and a type 956 buoy was used for the last 4 days. The main data acquisition system was a PC-based LabVIEW system. All sixty instrumentation channels were digitally sampled at 20 Hz. Time histories, statistical distributions and minimum and maximum values were determined and recorded.

For the present study only the ship motion and wave data have been used. A limited number of runs from the first three days of the trial was selected to satisfy the following 3 criteria:

- the significant wave height H_s is greater than 3 m,
- there is a clear dominant wave direction and minimal directional wave spreading,
- the nominal relative wave direction is oblique (bow quartering, beam, or stern quartering seas).

It was considered important to use runs with minimal directional wave spreading because the codes PRECAL and FREDYN give results only for unidirectional waves. Table 2 gives a summary of the runs selected for the present study.

3 Numerical Predictions

The numerical predictions were performed using the ship motion codes SHIPMO7 [2], PRECAL 4.0 [3], and FREDYN 8.2 [4].

3.1 SHIPMO7 Predictions

SHIPMO7 is the most recent version of DREA's frequency domain, strip theory code. SHIPMO was originally developed in the 1970's, and has since been continually used and improved. Validation of SHIPMO [1, 5, 6, 7] has shown that it gives good predictions of ship motions and sea loads within the limitations of linear strip theory. Among the codes tested here, SHIPMO7 is the only one that provides motion predictions in directional seas.

SHIPMO7 uses a linearization based on roll amplitude for computation of roll damping, with roll amplitude being solved in an iterative manner. For a ship in random long-crested waves, the roll amplitude at all wave frequencies is assumed to be 1.25 times the RMS roll displacement in the specified wave spectrum. For a

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***Table 2:** NIPIGON Trial Runs Used in Present Study*

Run	Speed (knots)	Wave heading	H_s (m)	T_z (s)	Wave direction (deg) Average	Deviation	Heading (deg)	Duration (min)
203	8	Bow	3.73	7.73	218.1	39.2	265	20
204	8	Quarter	3.67	7.21	224.9	38.6	85	20
206	16	Quarter	3.89	7.39	228.1	25.3	355	20
209	13	Bow	4.75	8.07	224.4	33.3	265	20
210	15	Quarter	4.75	8.07	224.4	33.3	85	20
303	8	Bow	5.82	9.45	274.3	41.4	310	20
304	8	Quarter	5.57	8.81	271.5	39.0	120	20
305	8	Bow	5.57	8.81	271.5	39.0	220	20
306	8	Quarter	5.16	8.66	266.0	45.3	50	20
309	14	Bow	5.39	8.95	278.6	32.2	315	20
310	14	Quarter	5.44	8.73	269.3	42.9	135	20
403	8	Bow	5.01	9.34	243.7	40.3	290	30
404	8	Quarter	4.90	9.60	237.6	47.0	110	30
409	16	Bow	4.52	8.37	237.6	50.3	285	30
410	16	Quarter	4.52	8.37	237.6	50.3	105	30
413	8	Beam	4.98	8.86	245.2	40.1	330	20

ship in random short-crested waves, the roll motions are evaluated using linear superposition using response amplitude operators (RAOs) from long-crested waves; thus, no further iteration is used for evaluating RAOs in short-crested waves.

For the present trials, SHIPMO7 predictions were made for NIPIGON in measured directional waves and for unidirectional waves approaching from the average wave direction given in Table 2. Annex A gives sample input for trial run 203 and a directional wave spectrum. SHIPMO7 ran without any problems for all cases. Due to motion resonance peaks, it was found that a wave frequency increment of 0.05 rad/s or lower should be used for SHIPMO7 computations for NIPIGON. For larger wave frequency increments, predicted RMS values and zero-crossing periods varied somewhat with the wave frequency increment value. Similar behaviour would be expected from any frequency domain ship motion program.

The SHIPMO7 predictions assumed negligible rudder motions.

3.2 PRECAL 4.0 Predictions

PRECAL is a linear, three-dimensional, frequency domain code that has been developed by the Cooperative Research Ships organization. PRECAL provides pressure predictions which can be used as input to structural analysis codes.

Earlier work at DREA [1, 5, 6, 7] found that PRECAL gave poor roll predictions when PRECAL computed its own roll damping coefficients. PRECAL gave better roll predictions when roll damping coefficients from SHIPMO7 were provided as input to PRECAL. For the current study using PRECAL 4.0, roll damping coefficients computed by PRECAL were used because an important objective was to assess the quality of roll predictions from each code.

The PRECAL suite includes three main programs. HYDMES generates a panel mesh for the ship hull. HYDCAL uses this mesh to compute hydrodynamic coefficients using a panel method. The program RESCAL uses these coefficients to generate motions, sea loads, and pressures in regular and long-crested random seaways.

Annex B gives sample input for RESCAL calculations. Compared to SHIPMO7, the RESCAL input appendage parameters used for roll damping calculations are less complete. The bilge keel location is based on only one lateral and vertical coordinate (bilge keel geometry assumed constant along the hull), and the longitudinal position is only crudely specified as being a forward or aft bilge keel. RESCAL includes no provision for modelling a skeg. Furthermore, there is no option to include two sets of aft fins to model the A-brackets supporting the propeller shafts. For the present study, the A-brackets were approximated using one set of fins located at a

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nominal position of the actual A-brackets, with a chord length selected to represented the total area of the A-brackets.

For many of the runs, RESCAL ran indefinitely, indicating a likely infinite loop. This problem was traced to lack of convergence in roll amplitude in subroutine ITERRND when computing motions in random seas. This problem was corrected by modifying subroutine ITERRND to incorporate a relaxation method for estimating roll amplitude after the first ten iterations. The relaxation method takes half of the current roll amplitude plus half of the previous roll amplitude for estimating the correct roll amplitude. This procedure was found to give rapid convergence for all cases with NIPIGON. The modified version of ITERRND ceases iteration if motion amplitudes fail to converge in a specified number of iterations. The revised code has been forwarded to Cooperative Research Ships. Subsequent investigation revealed that an error in the RESCAL code causes it to omit bilge keel damping forces, which causes particularly large errors in the vicinity of roll resonance.

Although PRECAL only computes motions in long-crested seas, motion predictions for measured directional seas were calculated for the present study using post-processing of RAOs computed in long-crested seas.

The PRECAL predictions assumed negligible rudder motions.

3.3 FREDYN 8.2 Predictions

FREDYN is a time domain strip theory code for predicting ship motions in waves and wind. FREDYN has been developed for the Cooperative Research Navies Dynamic Stability Project with the primary goal of predicting capsize of frigates in waves. The code includes maneuvering forces and can predict motions of both intact and damaged ships. FREDYN is limited to long-crested waves.

Annex C gives sample input for FREDYN calculations. Some minor problems were encountered with FREDYN documentation during preparation of input. For the CDAWSP input hull offset file "cda.inp", the second, third and fourth data spaces for hull offsets start in columns 5, 13, and 21 respectively rather than columns 9, 17, and 25, as stated in the manual [4]. For bilge keel input in FREINP input file "freinp.inp", the ship stations range from 1 at the aft-perpendicular to 21 at the fore-perpendicular. Station numbers elsewhere within FREDYN appear to range from 0 to 20. For the main FREDYN input file "fredyn.inp", setting the wave height parameter HWA to 0.0 in the WAVE1 record will cause no waves to be generated even if a user supplied wave spectrum is specified. This behaviour of the program is correctly documented and must be noted when specifying an input wave spectrum. In the OPTIONS record of FREDYN input, it is incorrectly stated that option PRIWAV will print wave spectrum data. In fact option PRIWAV1 must be

used to print the first wave system and option PRIWAV2 must be used to print the second wave system (if present).

Some resistance and propulsion characteristic of HMCS NIPIGON are classified and were not used in the present study. To circumvent this problem, resistance and propulsion parameters were taken from the MX frigate FREDYN example. For each ship speed during trials, the propeller RPM was set such that FREDYN gave the correct speed for NIPIGON. Figure 2 shows the variation of ship speed in calm water with propeller RPM as calculated by FREDYN. It is likely that usage of the MX frigate resistance and propulsion parameters had only a minor effect on predicted motions in waves. The autopilot coefficients for NIPIGON were also assumed to equal values for the MX frigate FREDYN example. Assumptions regarding the autopilot undoubtedly influenced the predicted ship motions. Although the SHIPMO7 and PRECAL predictions assume zero rudder motions, it was necessary for FREDYN to include rudder motions to maintain course.

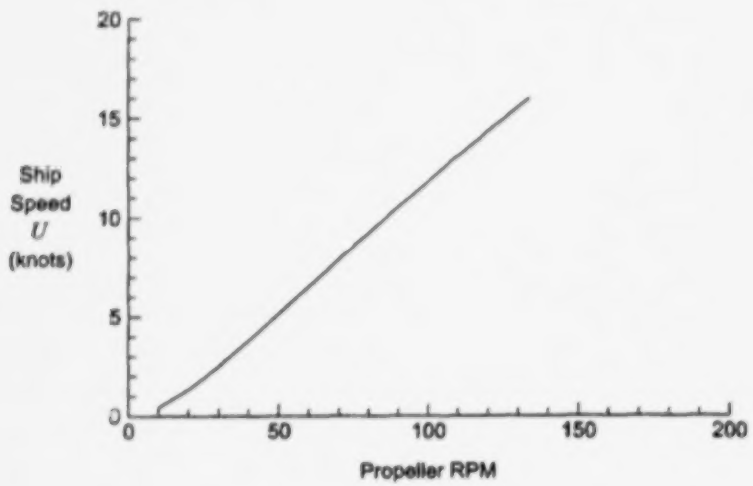

***Figure 2:** Ship Speed versus Propeller RPM for HMCS NIPIGON Using Assumed Resistance and Propulsion Characteristics*

Long-crested user-defined wave spectra were used for the FREDYN simulations. For each trial condition, the wave spectrum was represented using 37 wave frequency components, ranging from 0.2 to 2.0 rad/s with an increment of 0.05 rad/s.

4 Analysis of Wave Buoy Data and Numerical Predictions

Results from numerical predictions can vary with the methods of analysis used. This section describes analysis methods that were used in the present study.

Most of the analysis was done using the Python programming language, which is described in References 8 and 9. Python is a high-level, object-oriented language which is well suited to numerical applications. The Numerical Python extension module described in Reference 10 was used in the present work.

4.1 Wave Buoy Spectra

During the NIPIGON trial, directional wave spectra were measured using Endeco 956 and 1156 wave buoys. The measured directional wave spectral data required a correctional procedure due to the relatively low resolution of output directional spectral densities. For each discretized combination of wave frequency and direction, the output normalized spectral density has a range of 0 to 50. The wave buoy output file also gives the spectral density value associated with the normalized maximum of 50. Analysis of several wave buoy output files indicated that the output normalized spectral densities are likely rounded downward (e.g., a normalized density of 4.95 would be rounded downward to 4). To circumvent errors introduced by rounding all values downward, the following two step procedure was applied to normalized spectral densities:

- to compensate for rounding downward, 0.5 was added to each non-zero value of normalized spectral density,
- for each frequency band, a correction factor near unity was applied to all directional spectral densities such that the sum of the directional values equaled the output total energy for the frequency band.

The second step of the above procedure utilized non-directional spectral densities in the wave buoy output file, which were given to adequate resolution.

4.2 Ship Motion Encounter Spectra from Frequency Domain RAOs

Motion encounter spectra were generated for measured and predicted heave, roll and pitch motions. The motion encounter spectra were produced from frequency

domain RAOs as follows:

$$S_{\eta_i}(\omega_e) = \int_0^\infty S(\omega, \beta_s) \; |\eta_i'(\omega, \beta_s)|^2 \left| \frac{d\omega}{d\omega_e} \right| d\beta_s \tag{1}$$

where $S_{\eta_i}(\omega_e)$ is motion spectral density for mode i at encounter frequency ω_e, $S(\omega, \beta_s)$ is directional wave spectral density for wave frequency ω and sea direction β_s relative to the ship, and $\eta_i'(\omega, \beta_s)$ is motion amplitude for mode i in unit amplitude waves. Figure 3 gives the SHIPMO convention for relative sea direction. When analysing trial results, the directional wave spectrum is given according to absolute directions (from), and the ship is travelling at a known absolute heading, with true north being zero degrees. Figure 4 gives the absolute direction conventions. The relative sea direction for a wave component is given by:

$$\beta_s = \nu + 180^\circ - \chi \tag{2}$$

where ν is the wave component direction (from) and χ is the ship heading.

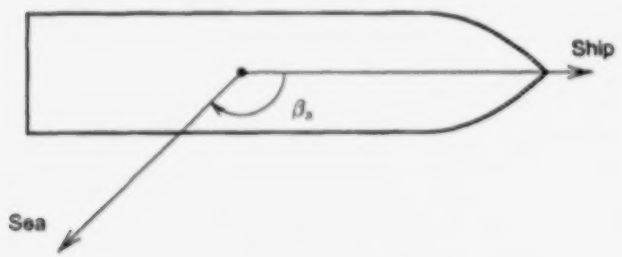

***Figure 3:** Definition of Sea Direction Relative to Ship Heading*

The most challenging part in evaluating the motion encounter spectrum of Equation (1) is determining the wave frequency (or frequencies) associated with a given encounter frequency. The encounter frequency is a function of wave frequency as follows:

$$\omega_e = \left| \omega - \frac{\omega^2}{g} U \cos\beta_s \right| \text{ for } U \cos\beta_s < 0 \tag{3}$$

where U is forward ship speed. For a ship in beam seas or for the ship at zero speed, the wave frequency is merely given by:

$$\omega(\omega_e) = \omega_e \text{ for } U \cos\beta_s = 0 \tag{4}$$

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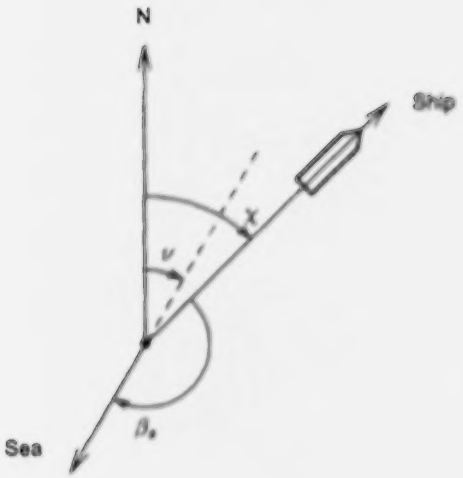

***Figure 4:** Definition of Sea Direction and Ship Heading Relative to True North*

For a ship in waves from ahead ($U \cos \beta_e < 0$), the left hand side of Equation (3) is always positive, and the wave frequency corresponding to a given encounter frequency is:

$$\omega(\omega_e) = \frac{g}{2U \cos \beta_e} \left(1 - \sqrt{1 - 4\omega_e \frac{U \cos \beta_e}{g}}\right) \text{ for } U \cos \beta_e < 0 \quad (5)$$

For a ship in waves from aft ($U \cos \beta_e > 0$), the situation becomes more complex because up to 3 different wave frequencies can be associated with a given encounter frequency. Figure 5 shows the variation of wave encounter frequency for wave frequency for a ship travelling at 20 knots in following seas. The following solution for wave frequency always exists for waves from aft:

$$\omega_1(\omega_e) = \frac{g}{2U \cos \beta_e} \left(1 + \sqrt{1 + 4\omega_e \frac{U \cos \beta_e}{g}}\right) \text{ for } U \cos \beta_e > 0 \quad (6)$$

At this point, a critical encounter frequency for waves from aft is introduced.

$$\omega_e^* = \frac{g}{4U \cos \beta_e} \text{ for } U \cos \beta_e > 0 \quad (7)$$

If the encounter frequency is less than the critical encounter frequency ω_e^*, then the following solutions also exist for wave frequencies associated with a given encounter frequency:

$$\omega_2(\omega_e) = \frac{g}{2U \cos \beta_e} \left(1 - \sqrt{1 - 4\omega_e \frac{U \cos \beta_e}{g}}\right) \text{ for } \omega_e \leq \omega_e^* \quad (8)$$

$$\omega_3(\omega_e) = \frac{g}{2U\cos\beta_s}\left(1 + \sqrt{1 - 4\omega_e\frac{U\cos\beta_s}{g}}\right) \text{ for } \omega_e \leq \omega_e^* \qquad (9)$$

If all 3 wave frequency solutions exist for a ship in waves from aft, then their contributions must all be summed when computing motion encounter spectra.

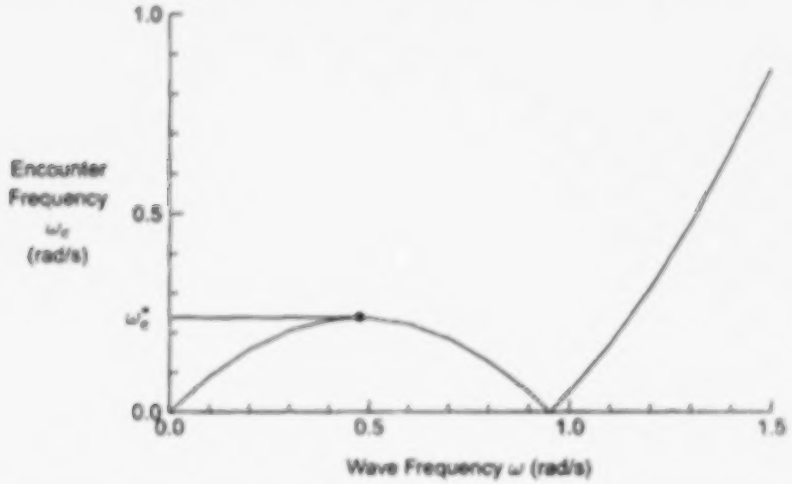

Figure 5: Wave Encounter Frequency Versus Wave Frequency for Ship Speed of 20 knots and Following Seas

To verify that encounter spectra were computed correctly, comparisons were made of RMS values and zero-crossing periods obtained by integration over encounter frequency and wave frequency. Relevant spectral moments from integration over encounter frequency are:

$$m_{0,i} = \int_0^\infty S_{\eta_i}(\omega_e)\, d\omega_e \qquad (10)$$

$$m_{2,i} = \int_0^\infty S_{\eta_i}(\omega_e)\, \omega_e^2\, d\omega_e \qquad (11)$$

where $m_{0,i}$ is the order zero moment for mode i and $m_{2,i}$ is the second moment for mode i. The same values can be obtained from integration over wave frequency as follows:

$$m_{0,i} = \int_0^\infty S_{\eta_i}(\omega) d\omega \qquad (12)$$

$$m_{2,i} = \int_0^\infty S_{\eta_i}(\omega)\omega_e^2(\omega) d\omega \qquad (13)$$

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RMS response and zero-crossing wave period for mode i are given by:

$$\sigma_i = \sqrt{m_{0,i}} \tag{14}$$

$$T_{z,i} = 2\pi \sqrt{\frac{m_{0,i}}{m_{2,i}}} \tag{15}$$

Note that integration over wave frequency is simpler and is the method typically used by frequency domain ship motion codes to obtain motion statistics. With the current motion predictions, integration over the computed encounter frequency spectra gives the same values as integration over wave frequency, suggesting that the encounter frequency spectra are correct. Due to the possibility of narrow peaks in encounter spectra, it was found that the encounter frequency increment should be 0.02 rad/s or less.

4.3 Encounter Spectra from Measured Ship Motions

During sea trials, the roll angle, pitch angle and vertical acceleration were measured using the DREA ship motions package, which was positioned near the ship CG. Heave acceleration at the ship CG was obtained using a transformation of the measured motions. Time series were recorded digitally using a PC-based LabVIEW multi-channel data acquisition system sampling at 20 Hz. Encounter spectra were obtained from single fast Fourier transforms of times series containing 24000 to 36000 samples, depending on the run length, using IDL Version 5.0. Heave displacements were derived from measured accelerations by integration in the frequency domain. Measured encounter spectra were smoothed by summation of spectral energy in bands of approximately 0.05 rad/s wide.

4.4 Encounter Spectra from FREDYN Predictions

Encounter spectra from FREDYN predictions were obtained using fast Fourier transforms from the function real_fft of the Numeric Python library, which is documented in Reference 10. Encounter spectral densities are calculated as follows:

$$S_{\eta_a}(\omega_{e,j}) = 2\left(\frac{A_j}{n_t}\right)^2 \frac{1}{\Delta\omega_e} \tag{16}$$

where A_j are Fourier coefficients from function real_fft, n_t is the number of samples in the time series, and $\Delta\omega_e$ is the frequency increment of the Fourier coefficients. The frequency increment, maximum frequency, and frequency of spectral components are:

$$\Delta\omega_e = \frac{\omega_{e,max}}{n_{\omega_e} - 1} \tag{17}$$

$$\omega_{e,max} = \frac{\pi}{\Delta t} \tag{18}$$

$$\omega_{e,j} = (j-1)\Delta\omega_e \text{ for } j = 1, 2, ..., n_{\omega_e} \tag{19}$$

where n_{ω_e} is the number of spectral components A_j, and Δt is the sampling interval in seconds of the time series.

Because FREDYN simulates a random wave spectrum using discretized wave components, the resulting motion encounter spectra had very pronounced peaks at encounter frequencies corresponding to the individual wave components. To estimate motion responses in a smooth wave spectrum, the triangular smoothing function shown in Figure 6 was applied to the computed motion encounter spectra. A smoothing bandwidth $\delta\omega_e$ of 0.1 rad/s, twice the increment of 0.05 rad/s between individual wave components, gave good results.

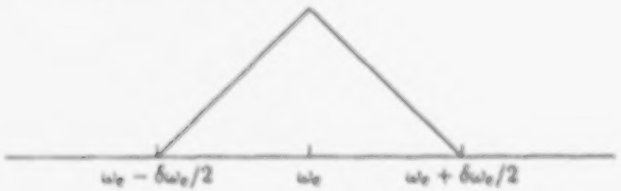

***Figure 6**: Triangular Smoothing Function for Encounter Spectra from FREDYN*

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5 Presentation of Measured and Predicted Motions

Tables 3 to 8 give observed and predicted values for RMS motion and zero-crossing period for heave, roll, and pitch. Figures 7 to 22 give wave spectra and motion encounter spectra. Tables 3 to 8 include summary statistics of the ratio of observed to predicted RMS and zero-crossing period values. The summary statistics include values for long-crested sea predictions that have been corrected for directional effects as follows:

$$\text{Directional prediction} = \text{Long-crested prediction} \times \frac{\text{SHIPMO7 directional}}{\text{SHIPMO7 long-crested}} \quad (20)$$

The SHIPMO7 predictions are used to apply the directional correction because SHIPMO7 gives good agreement with observed motions.

Figures 7 to 22 include point spectral densities and directional distributions for wave energy. The y values for the directional distributions are fraction of energy for each 10 degree direction increment. To reduce clutter, the figures of motion encounter spectra do not include PRECAL predictions for long-crested seas. The remaining encounter spectra are considered to be sufficient for indicating all relevant trends in the spectral data. Many of the pronounced peaks in the PRECAL predictions are considered erroneous due to the absence of bilge keel damping forces; thus, the PRECAL data were not considered when selecting appropriate scales for each plot.

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Table 3: RMS Heave (m)

Run	Observed	SHIPMO7 Dir.	PRECAL Dir.	SHIPMO7 Long-cr.	PRECAL Long-cr.	FREDYN (Long-cr.)
203	0.70	0.65	0.65	0.63	0.63	0.60
204	0.55	0.48	0.47	0.43	0.41	0.43
206	0.76	0.60	0.59	0.51	0.48	0.48
209	0.84	0.90	0.91	0.83	0.85	0.82
210	0.89	0.71	0.69	0.60	0.57	0.57
303	1.38	1.10	1.10	1.11	1.11	1.05
304	1.02	0.93	0.92	0.86	0.84	0.84
305	0.98	1.19	1.19	1.12	1.12	1.05
306	0.81	0.97	0.96	0.80	0.78	0.79
309	1.33	1.07	1.08	1.05	1.06	1.02
310	0.97	0.92	0.90	0.91	0.89	0.87
403	1.15	1.00	1.00	1.01	1.01	0.96
404	0.88	0.93	0.92	0.96	0.95	0.95
409	1.13	0.88	0.89	0.96	0.97	0.94
410	0.78	0.74	0.73	0.73	0.71	0.70
413	1.09	1.14	1.14	1.28	1.26	1.17
Predicted/observed						
Mean		0.94	0.93	0.90	0.89	0.87
Deviation		0.14	0.14	0.15	0.15	0.14
Predicted/observed corrected for directional effects						
Mean		0.94	0.93	0.94	0.93	0.90
Deviation		0.14	0.14	0.14	0.14	0.13

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***Table 4:** Heave Zero-Crossing Period (s)*

Run	Observed	SHIPMO7 Dir.	PRECAL Dir.	SHIPMO7 Long-cr.	PRECAL Long-cr.	FREDYN (Long-cr.)
203	8.12	8.37	8.36	8.05	8.02	8.05
204	9.29	10.33	10.24	12.63	12.64	12.33
206	11.83	10.48	10.36	14.18	14.26	14.01
209	7.29	7.01	7.00	6.76	6.76	6.57
210	11.69	11.98	11.88	16.03	16.07	15.79
303	9.71	9.77	9.74	9.41	9.36	9.45
304	12.16	13.30	13.28	14.92	14.96	14.40
305	8.64	8.66	8.58	9.05	8.99	9.21
306	11.09	10.78	10.69	14.08	14.13	13.43
309	9.62	8.15	8.11	7.84	7.79	7.52
310	11.73	13.29	13.24	16.17	16.25	16.07
403	9.98	9.54	9.50	9.41	9.37	9.38
404	11.17	12.33	12.29	13.36	13.38	12.77
409	8.29	7.55	7.50	7.08	7.06	6.73
410	11.31	12.20	12.07	16.65	16.72	16.29
413	10.22	8.80	8.74	8.47	8.57	8.72
Predicted/observed						
Mean		1.00	0.99	1.12	1.12	1.10
Deviation		0.09	0.09	0.21	0.21	0.20
Predicted/observed corrected for directional effects						
Mean		1.00	0.99	1.00	1.00	0.98
Deviation		0.09	0.09	0.09	0.09	0.09

***Table 5:** RMS Roll (m)*

Run	Observed	SHIPMO7 Dir.	PRECAL Dir.	SHIPMO7 Long-cr.	PRECAL Long-cr.	FREDYN (Long-cr.)
203	2.83	3.33	8.88	3.06	4.52	4.07
204	3.97	4.35	17.66	5.04	35.67	7.36
206	4.25	5.43	14.77	6.75	14.43	10.25
209	2.64	2.51	5.91	1.85	2.37	3.18
210	4.98	5.27	16.79	4.33	4.38	7.94
303	4.95	5.15	26.11	5.70	27.25	6.36
304	6.16	4.98	30.94	5.15	18.66	7.46
305	3.18	5.27	21.97	5.92	9.80	6.59
306	4.46	6.18	31.74	5.90	28.05	8.81
309	3.93	3.30	8.29	3.03	4.87	4.24
310	5.41	4.12	7.79	5.65	6.45	8.05
403	3.95	4.53	22.03	5.58	10.40	6.12
404	4.26	4.78	26.57	6.28	27.84	8.58
409	2.63	2.57	5.36	2.79	4.65	3.98
410	3.75	3.75	8.13	4.71	4.78	8.66
413	4.24	6.05	23.67	6.98	22.54	7.04
Predicted/observed						
Mean		1.11	4.13	1.21	3.35	1.67
Deviation		0.23	1.81	0.32	2.38	0.39
Predicted/observed corrected for directional effects						
Mean		1.11	4.13	1.11	3.02	1.54
Deviation		0.23	1.81	0.23	2.07	0.31

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***Table 6:** Roll Zero-Crossing Period (s)*

Run	Observed	SHIPMO7 Dir.	PRECAL Dir.	SHIPMO7 Long-cr.	PRECAL Long-cr.	FREDYN (Long-cr.)
203	9.21	9.69	10.30	9.27	9.71	9.50
204	10.19	10.53	10.62	10.50	10.56	10.34
206	12.29	11.17	10.88	13.05	13.07	13.04
209	8.44	8.42	9.76	7.44	7.97	8.72
210	12.26	11.96	10.58	15.45	15.45	15.32
303	9.51	10.57	10.57	10.21	10.70	10.26
304	10.97	10.86	10.57	10.99	10.70	10.68
305	8.85	10.01	10.51	10.07	10.33	9.78
306	10.71	10.43	10.54	10.97	10.78	10.78
309	9.12	9.56	10.21	9.32	9.79	9.57
310	11.49	12.35	11.16	13.49	13.36	13.43
403	9.97	10.28	10.54	10.18	10.54	10.06
404	10.68	10.73	10.56	10.78	10.42	10.62
409	9.52	9.67	10.18	8.90	9.48	9.33
410	12.06	12.99	11.48	14.73	14.70	14.52
413	9.98	10.15	10.50	10.33	10.29	10.75
Predicted/observed						
Mean		1.03	1.03	1.06	1.07	1.06
Deviation		0.05	0.09	0.10	0.09	0.08
Predicted/observed corrected for directional effects						
Mean		1.03	1.03	1.03	1.04	1.04
Deviation		0.05	0.09	0.05	0.07	0.07

Table 7: RMS Pitch (m)

Run	Observed	SHIPMO7 Dir.	PRECAL Dir.	SHIPMO7 Long-cr.	PRECAL Long-cr.	FREDYN (Long-cr.)
203	1.03	1.14	1.18	1.39	1.42	1.26
204	0.79	0.93	0.90	0.98	0.93	0.92
206	1.00	1.01	0.92	1.08	0.90	0.85
209	1.45	1.83	1.92	2.03	2.13	1.74
210	1.08	1.23	1.15	1.32	1.21	1.15
303	1.66	1.98	2.06	2.12	2.19	1.91
304	1.51	1.39	1.34	1.53	1.47	1.40
305	1.89	1.72	1.81	1.94	1.98	1.71
306	1.44	1.34	1.33	1.46	1.39	1.33
309	1.59	1.84	1.95	2.05	2.16	1.79
310	1.21	1.31	1.27	1.41	1.28	1.16
403	1.37	1.64	1.71	1.69	1.73	1.55
404	1.08	1.29	1.28	1.28	1.23	1.15
409	1.59	1.62	1.72	1.76	1.85	1.54
410	1.04	1.13	1.11	1.16	1.04	1.01
413	1.10	1.21	1.27	0.43	0.42	0.69
Predicted/observed						
Mean		1.09	1.10	1.13	1.11	1.02
Deviation		0.10	0.13	0.22	0.25	0.15
Predicted/observed corrected for directional effects						
Mean		1.09	1.10	1.09	1.07	1.01
Deviation		0.10	0.13	0.10	0.14	0.21

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Table 8: *Pitch Zero-Crossing Period (s)*

Run	Observed	SHIPMO7 Dir.	PRECAL Dir.	SHIPMO7 Long-cr.	PRECAL Long-cr.	FREDYN (Long-cr.)
203	6.30	7.25	7.24	6.70	6.70	6.75
204	7.94	10.02	9.88	11.37	11.41	11.18
206	12.10	11.63	11.65	13.48	13.59	13.58
209	5.80	6.19	6.19	6.18	6.19	6.02
210	10.06	13.59	13.53	15.68	15.71	15.58
303	7.26	7.83	7.87	7.70	7.73	7.86
304	10.84	12.54	12.56	13.20	13.30	12.81
305	7.29	7.00	6.91	6.79	6.81	6.83
306	11.37	10.78	10.47	12.43	12.52	11.84
309	6.66	6.29	6.33	6.30	6.33	6.46
310	10.31	14.13	13.88	14.60	14.75	14.81
403	7.69	7.55	7.52	7.54	7.56	7.74
404	9.15	11.59	11.45	11.26	11.32	10.37
409	6.46	5.95	5.94	5.86	5.88	5.90
410	10.18	12.64	12.19	15.42	15.55	15.13
413	7.97	7.25	7.09	5.97	6.15	6.49
Predicted/observed						
Mean		1.10	1.09	1.14	1.15	1.14
Deviation		0.16	0.15	0.23	0.23	0.21
Predicted/observed corrected for directional effects						
Mean		1.10	1.09	1.10	1.11	1.09
Deviation		0.16	0.15	0.16	0.16	0.14

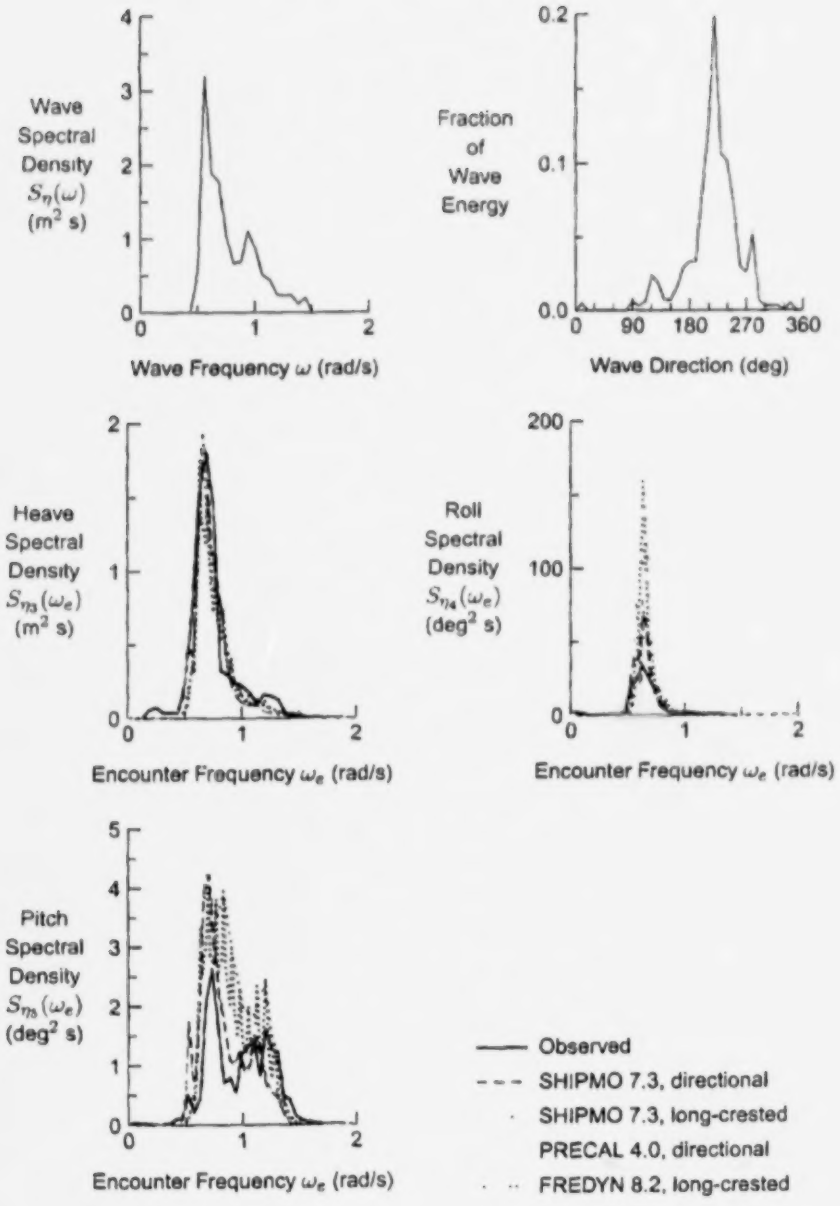
Wave Spectral Density $S_\eta(\omega)$ (m^2 s)
Wave Frequency ω (rad/s)
Fraction of Wave Energy
Wave Direction (deg)
Heave Spectral Density $S_{\eta_3}(\omega_e)$ (m^2 s)
Encounter Frequency ω_e (rad/s)
Roll Spectral Density $S_{\eta_4}(\omega_e)$ (deg^2 s)
Encounter Frequency ω_e (rad/s)
Pitch Spectral Density $S_{\eta_5}(\omega_e)$ (deg^2 s)
Encounter Frequency ω_e (rad/s)
Observed
SHIPMO 7.3, directional
SHIPMO 7.3, long-crested
PRECAL 4.0, directional
FREDYN 8.2, long-crested

Figure 7: *Wave and Motion Spectra for Run 203, 8 knots, Bow Quartering Seas*

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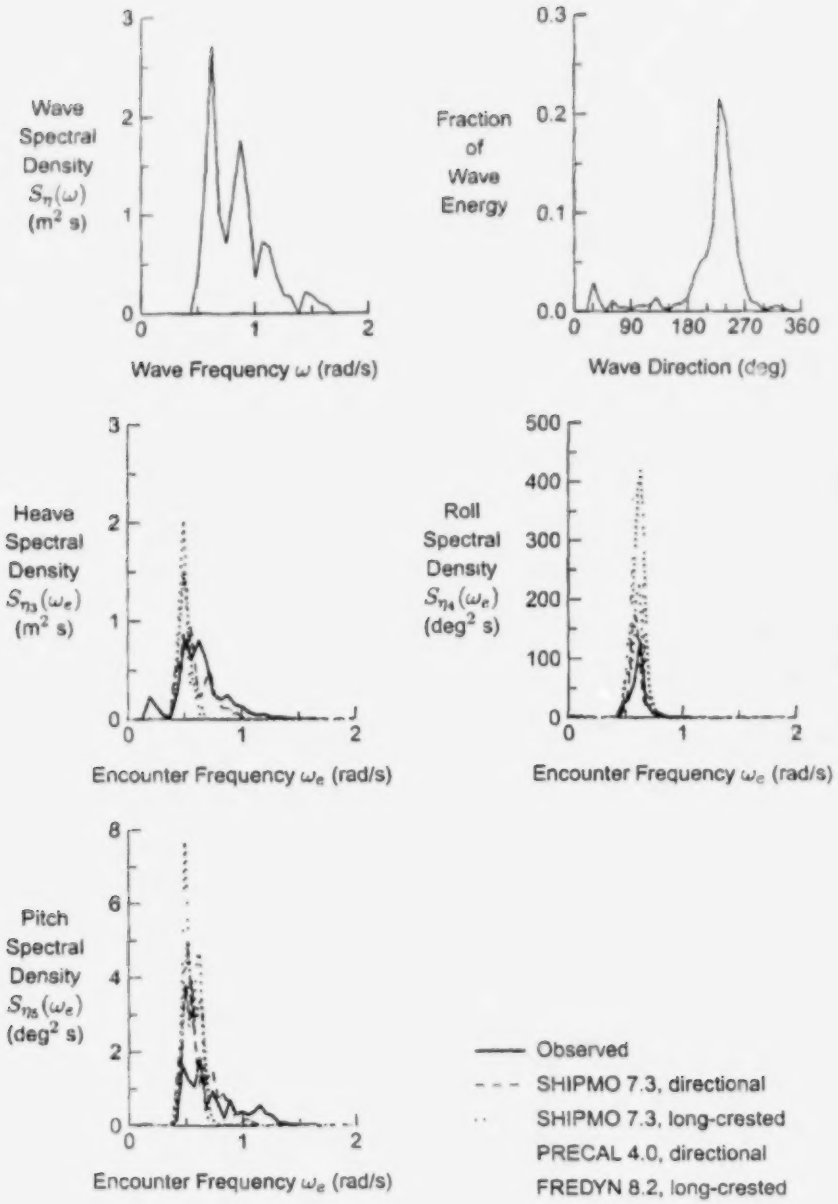
Wave Spectral Density $S_\eta(\omega)$ (m^2 s)
Wave Frequency ω (rad/s)
Fraction of Wave Energy
Wave Direction (deg)
Heave Spectral Density $S_{\eta_3}(\omega_e)$ (m^2 s)
Encounter Frequency ω_e (rad/s)
Roll Spectral Density $S_{\eta_4}(\omega_e)$ (deg^2 s)
Encounter Frequency ω_e (rad/s)
Pitch Spectral Density $S_{\eta_5}(\omega_e)$ (deg^2 s)
Encounter Frequency ω_e (rad/s)
Observed
SHIPMO 7.3, directional
SHIPMO 7.3, long-crested
PRECAL 4.0, directional
FREDYN 8.2, long-crested

Figure 8: *Wave and Motion Spectra for Run 204, 8 knots, Stern Quartering Seas*

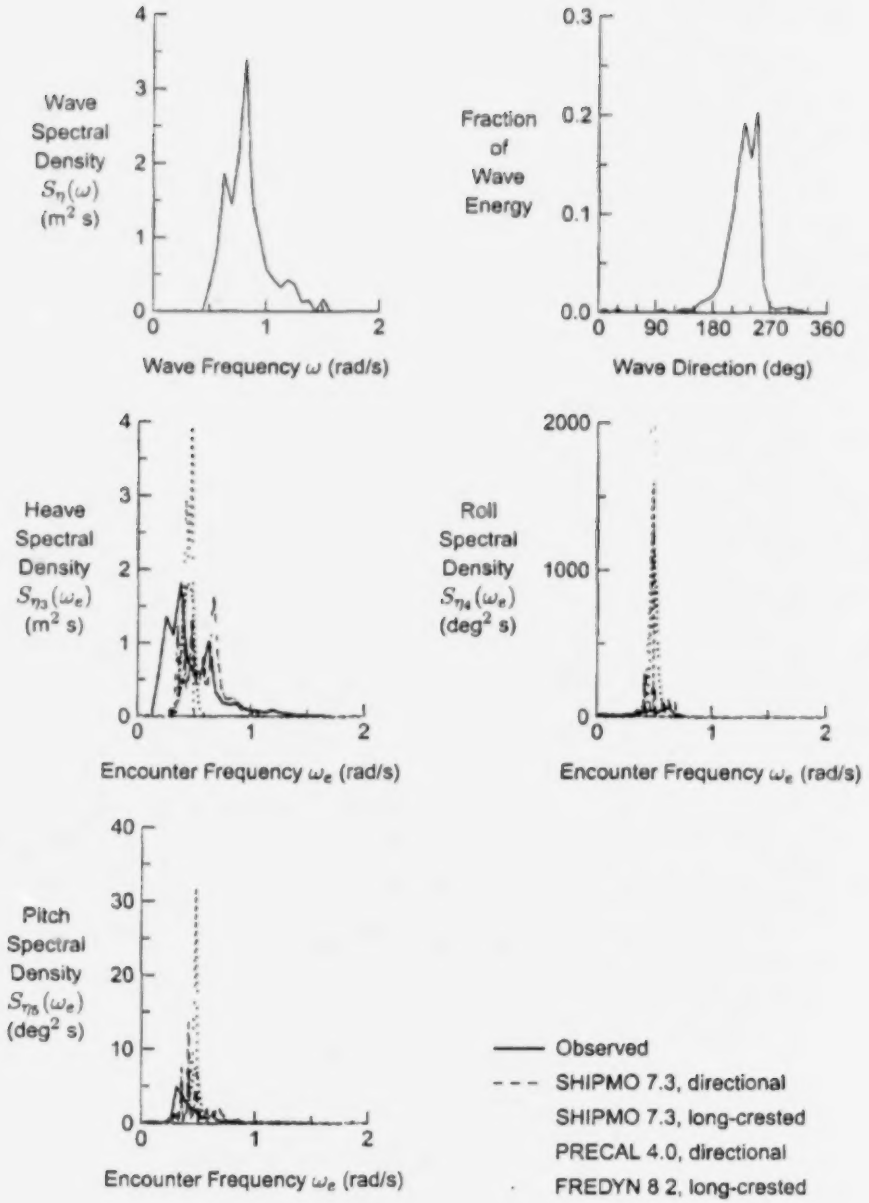
Wave Spectral Density $S_\eta(\omega)$ (m^2 s)
Wave Frequency ω (rad/s)
Fraction of Wave Energy
Wave Direction (deg)
Heave Spectral Density $S_{\eta_3}(\omega_e)$ (m^2 s)
Encounter Frequency ω_e (rad/s)
Roll Spectral Density $S_{\eta_4}(\omega_e)$ (deg^2 s)
Encounter Frequency ω_e (rad/s)
Pitch Spectral Density $S_{\eta_5}(\omega_e)$ (deg^2 s)
Encounter Frequency ω_e (rad/s)
Observed
SHIPMO 7.3, directional
SHIPMO 7.3, long-crested
PRECAL 4.0, directional
FREDYN 8.2, long-crested

***Figure 9**: Wave and Motion Spectra for Run 206, 16 knots, Stern Quartering Seas*

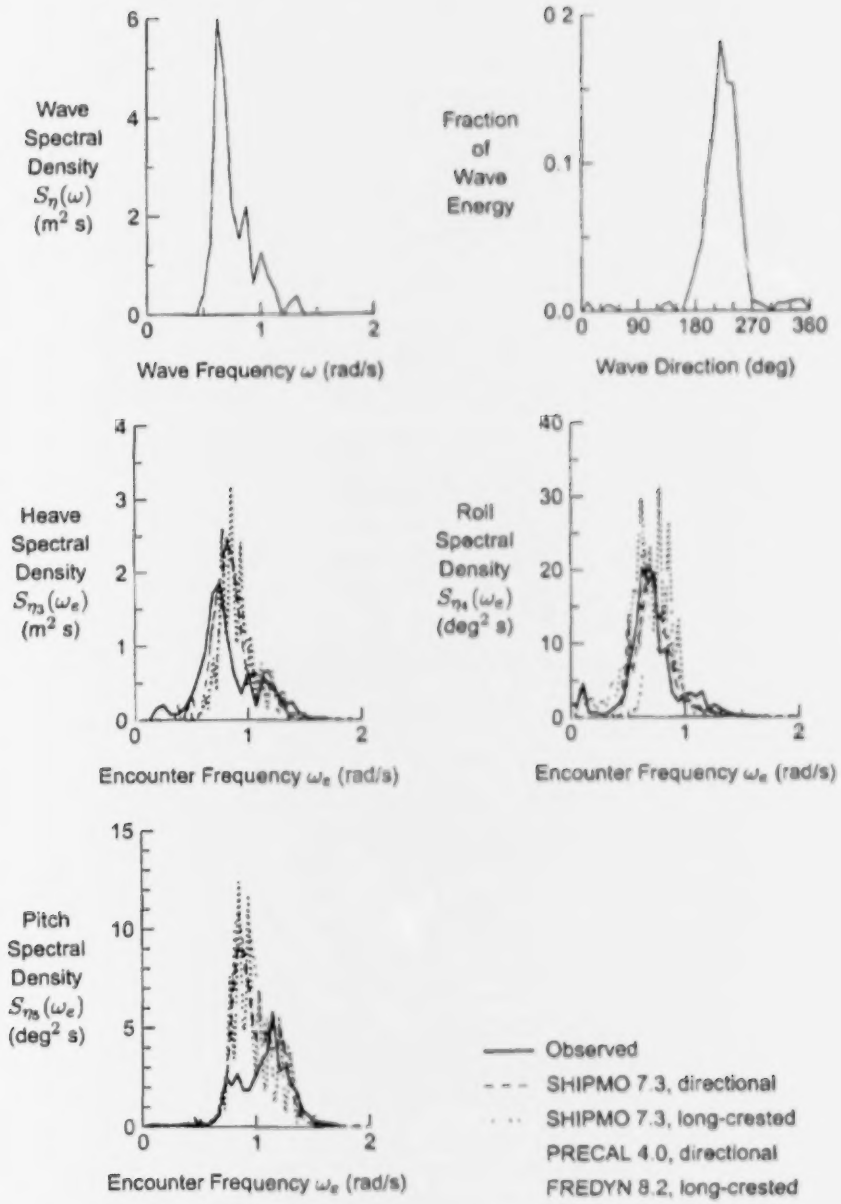
Wave Spectral Density $S_\eta(\omega)$ (m^2 s)
Wave Frequency ω (rad/s)
Fraction of Wave Energy
Wave Direction (deg)
Heave Spectral Density $S_{\eta_3}(\omega_e)$ (m^2 s)
Encounter Frequency ω_e (rad/s)
Roll Spectral Density $S_{\eta_4}(\omega_e)$ (deg^2 s)
Encounter Frequency ω_e (rad/s)
Pitch Spectral Density $S_{\eta_5}(\omega_e)$ (deg^2 s)
Encounter Frequency ω_e (rad/s)
Observed
SHIPMO 7.3, directional
SHIPMO 7.3, long-crested
PRECAL 4.0, directional
FREDYN 8.2, long-crested

***Figure 10**: Wave and Motion Spectra for Run 209, 13 knots, Bow Quartering Seas*

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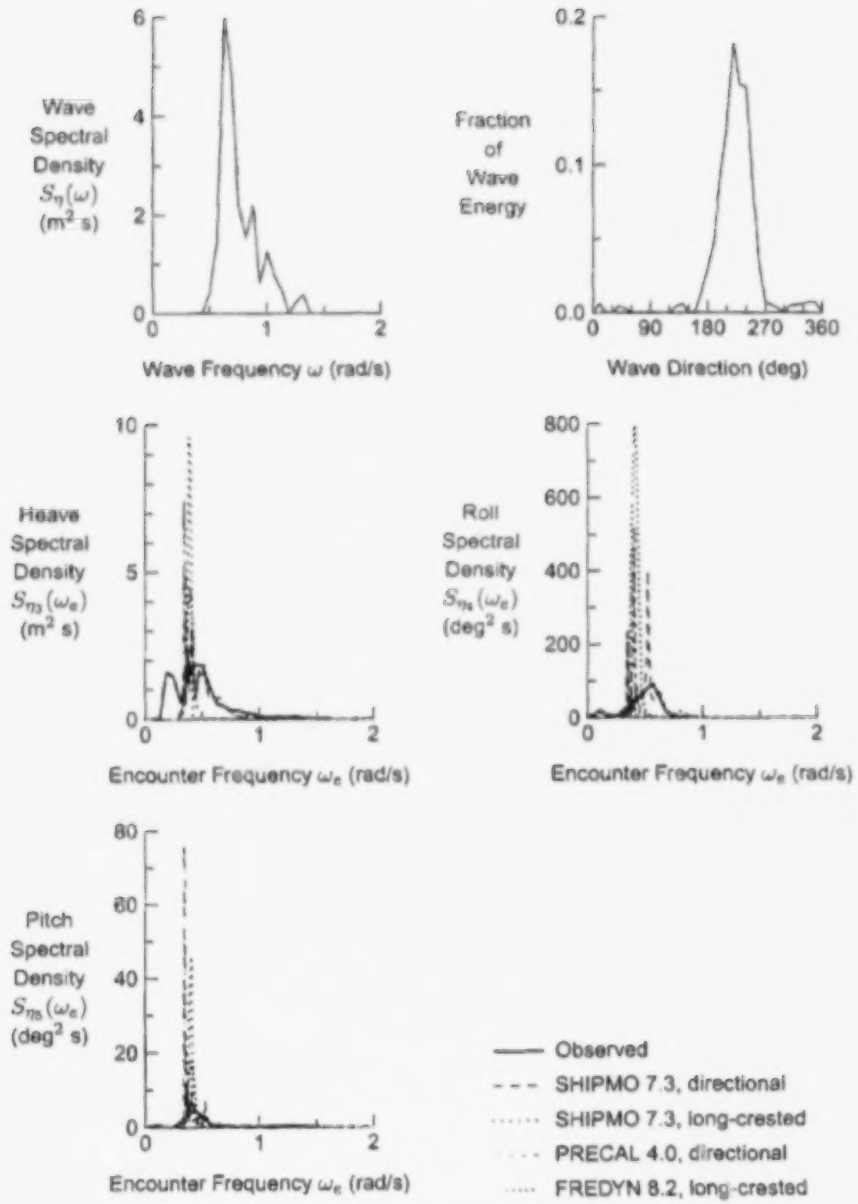
Wave Spectral Density $S_\eta(\omega)$ (m^2 s)
Wave Frequency ω (rad/s)
Fraction of Wave Energy
Wave Direction (deg)
Heave Spectral Density $S_{\eta 3}(\omega_e)$ (m^2 s)
Encounter Frequency ω_e (rad/s)
Roll Spectral Density $S_{\eta 4}(\omega_e)$ (deg^2 s)
Encounter Frequency ω_e (rad/s)
Pitch Spectral Density $S_{\eta 5}(\omega_e)$ (deg^2 s)
Encounter Frequency ω_e (rad/s)
Observed
SHIPMO 7.3, directional
SHIPMO 7.3, long-crested
PRECAL 4.0, directional
FREDYN 8.2, long-crested

***Figure 11**: Wave and Motion Spectra for Run 210, 15 knots, Stern Quartering Seas*

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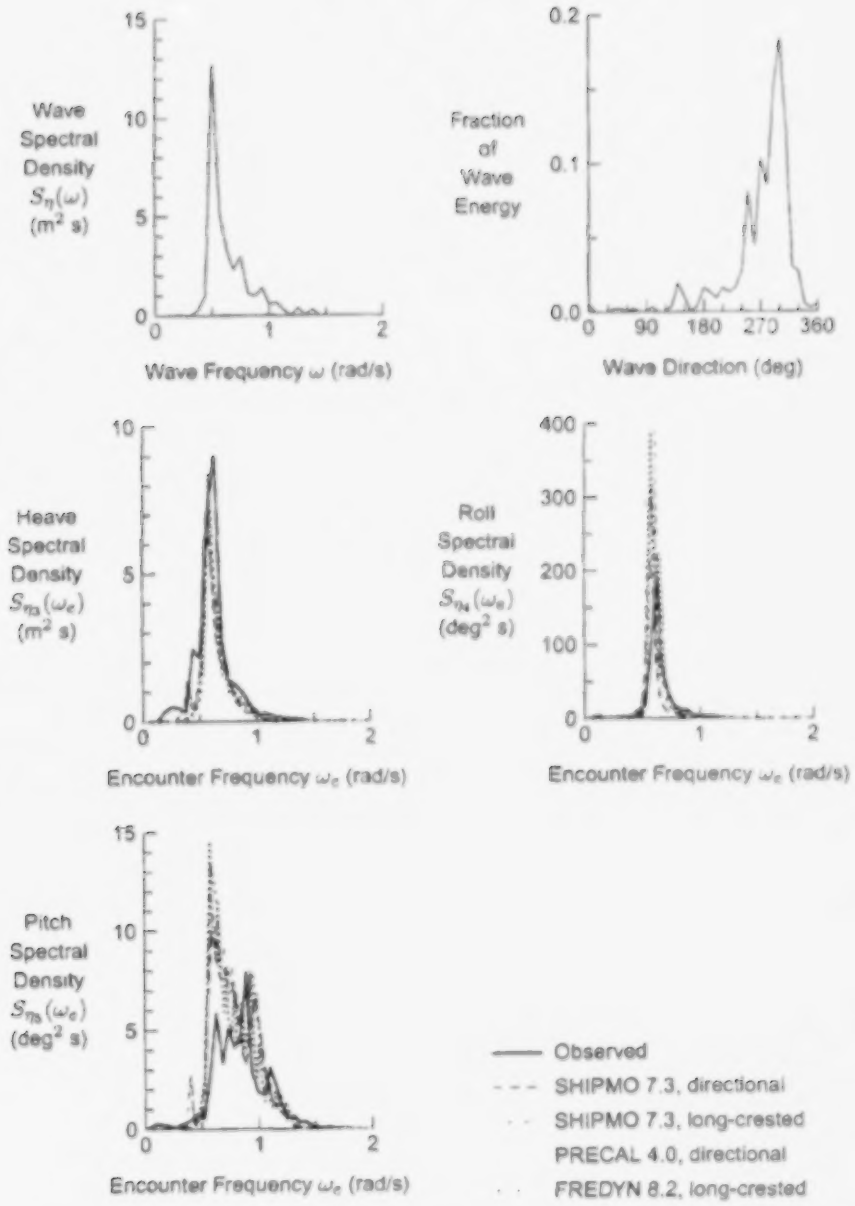
Wave Spectral Density $S_\eta(\omega)$ (m² s)
Wave Frequency ω (rad/s)
Fraction of Wave Energy
Wave Direction (deg)
Heave Spectral Density $S_{\eta_3}(\omega_e)$ (m² s)
Encounter Frequency ω_e (rad/s)
Roll Spectral Density $S_{\eta_4}(\omega_e)$ (deg² s)
Encounter Frequency ω_e (rad/s)
Pitch Spectral Density $S_{\eta_5}(\omega_e)$ (deg² s)
Encounter Frequency ω_e (rad/s)
Observed
SHIPMO 7.3, directional
SHIPMO 7.3, long-crested
PRECAL 4.0, directional
FREDYN 8.2, long-crested

***Figure 12**: Wave and Motion Spectra for Run 303, 8 knots, Bow Quartering Seas*

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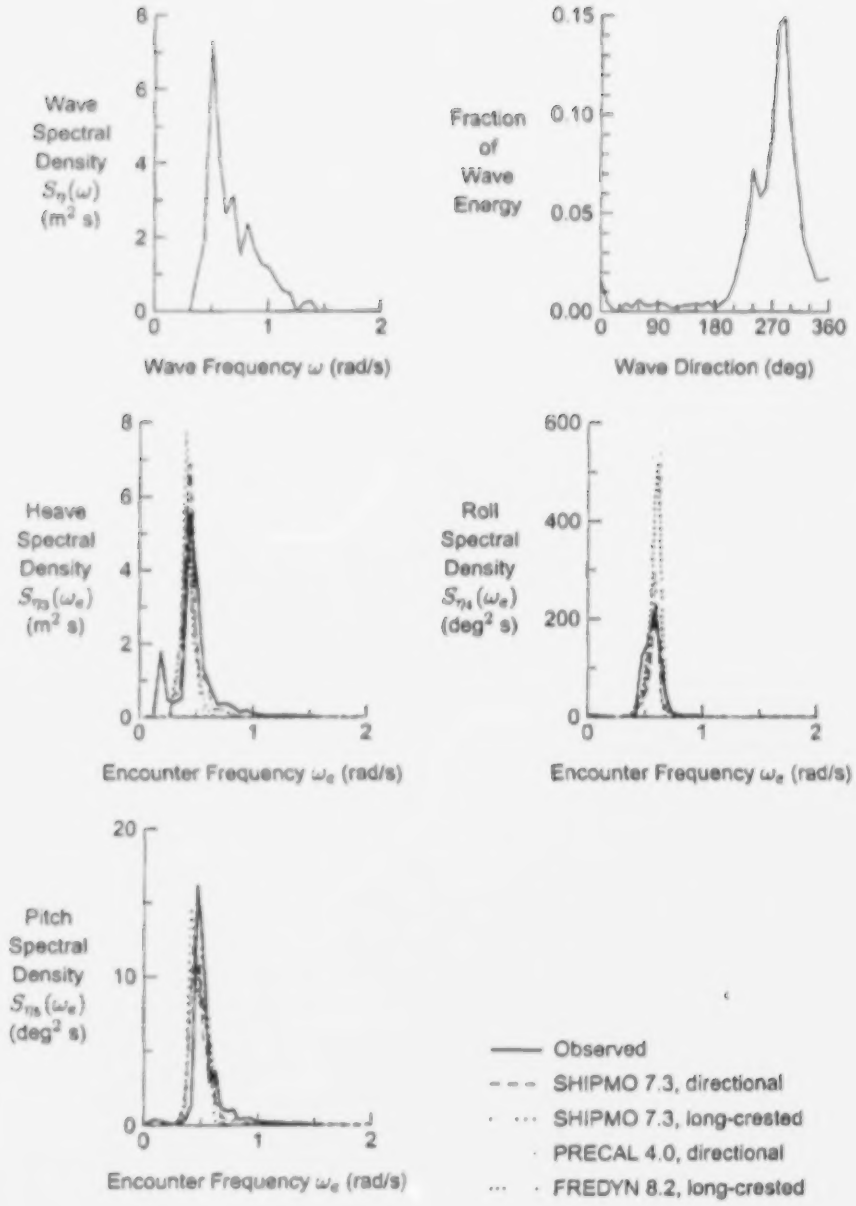
Wave Spectral Density $S_\eta(\omega)$ (m^2 s)
Wave Frequency ω (rad/s)
Fraction of Wave Energy
Wave Direction (deg)
Heave Spectral Density $S_{\eta 3}(\omega_e)$ (m^2 s)
Encounter Frequency ω_e (rad/s)
Roll Spectral Density $S_{\eta 4}(\omega_e)$ (deg^2 s)
Encounter Frequency ω_e (rad/s)
Pitch Spectral Density $S_{\eta 5}(\omega_e)$ (deg^2 s)
Encounter Frequency ω_e (rad/s)
Observed
SHIPMO 7.3, directional
SHIPMO 7.3, long-crested
PRECAL 4.0, directional
FREDYN 8.2, long-crested

***Figure 13:** Wave and Motion Spectra for Run 304, 8 knots, Stern Quartering Seas*

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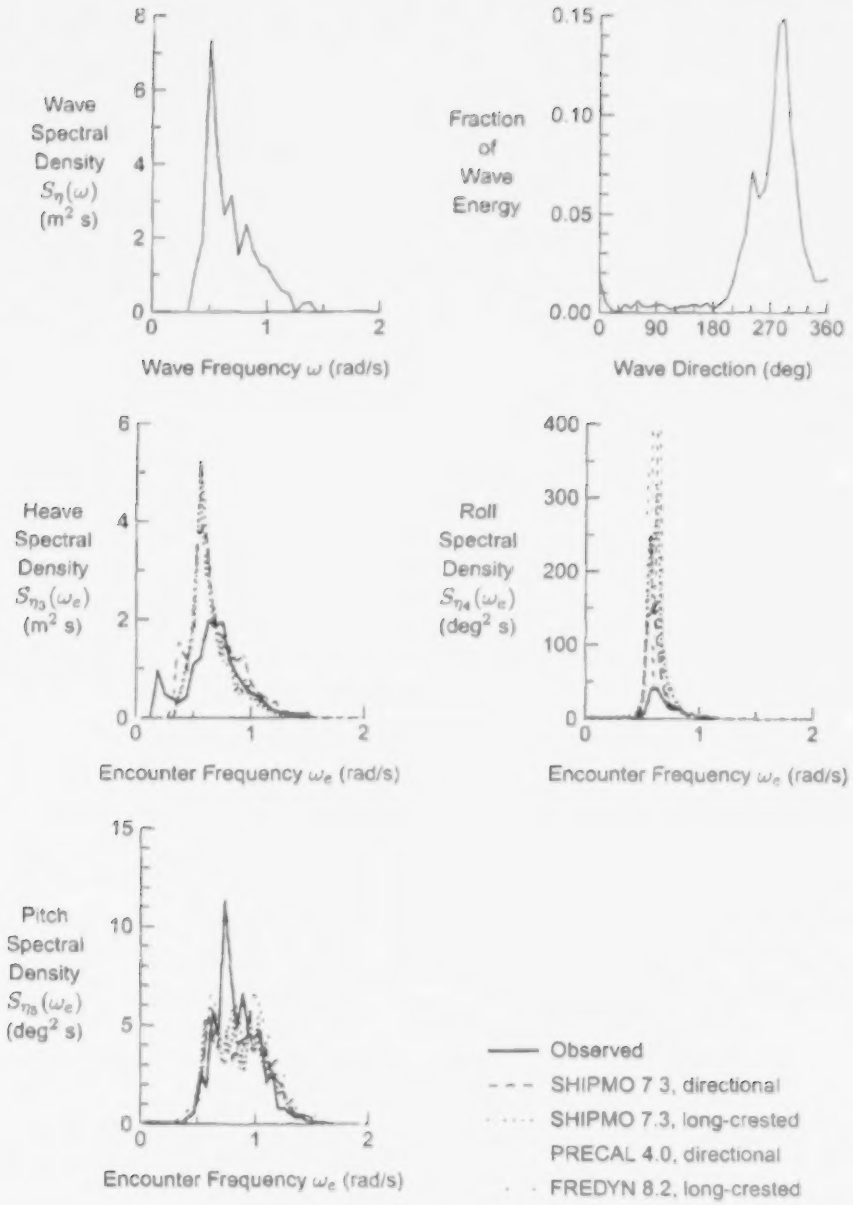
Wave Spectral Density $S_\eta(\omega)$ (m^2 s)
Wave Frequency ω (rad/s)
Fraction of Wave Energy
Wave Direction (deg)
Heave Spectral Density $S_{\eta_3}(\omega_e)$ (m^2 s)
Encounter Frequency ω_e (rad/s)
Roll Spectral Density $S_{\eta_4}(\omega_e)$ (deg^2 s)
Encounter Frequency ω_e (rad/s)
Pitch Spectral Density $S_{\eta_5}(\omega_e)$ (deg^2 s)
Encounter Frequency ω_e (rad/s)
Observed
SHIPMO 7.3, directional
SHIPMO 7.3, long-crested
PRECAL 4.0, directional
FREDYN 8.2, long-crested

Figure 14: *Wave and Motion Spectra for Run 305, 8 knots, Bow Quartering Seas*

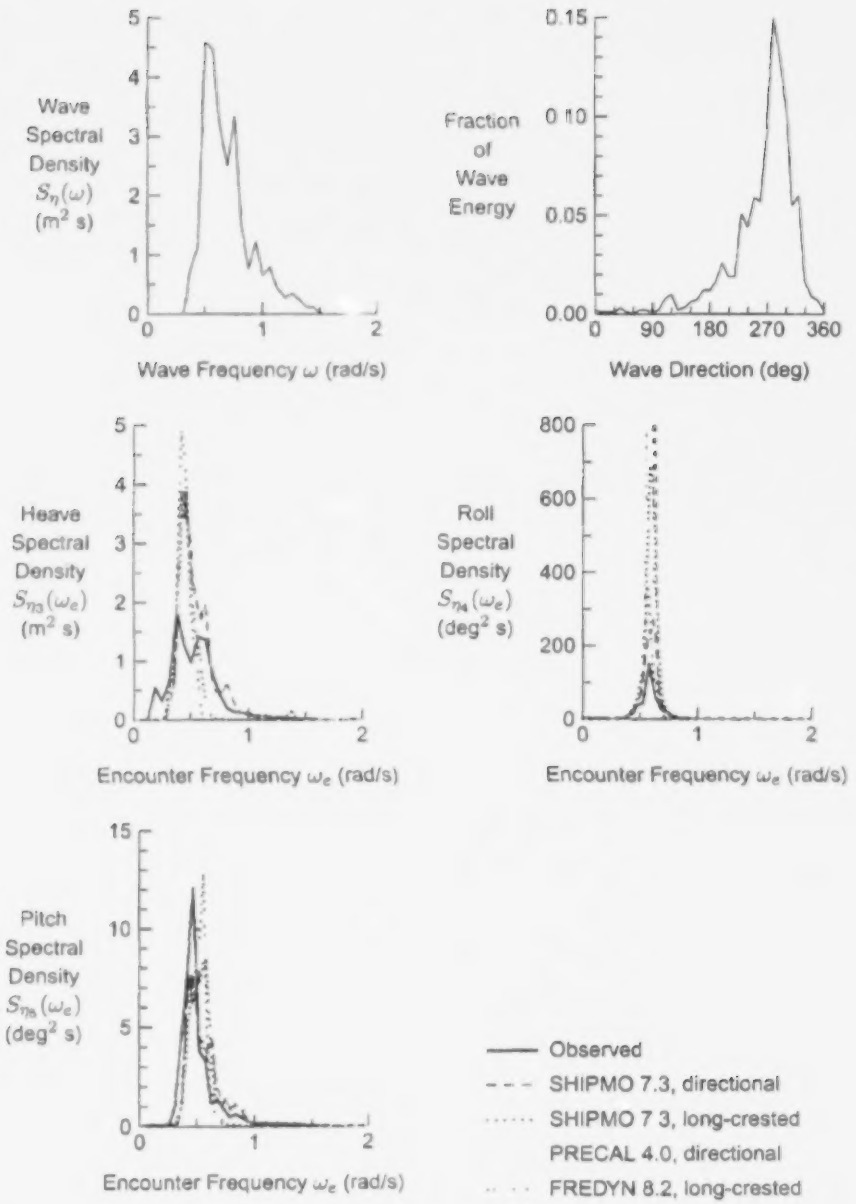
Wave Spectral Density $S_\eta(\omega)$ (m^2 s)
Wave Frequency ω (rad/s)
Fraction of Wave Energy
Wave Direction (deg)
Heave Spectral Density $S_{\eta 3}(\omega_e)$ (m^2 s)
Encounter Frequency ω_e (rad/s)
Roll Spectral Density $S_{\eta 4}(\omega_e)$ (deg^2 s)
Encounter Frequency ω_e (rad/s)
Pitch Spectral Density $S_{\eta 5}(\omega_e)$ (deg^2 s)
Encounter Frequency ω_e (rad/s)
Observed
SHIPMO 7.3, directional
SHIPMO 7.3, long-crested
PRECAL 4.0, directional
FREDYN 8.2, long-crested

Figure 15: *Wave and Motion Spectra for Run 306, 8 knots, Stern Quartering Seas*

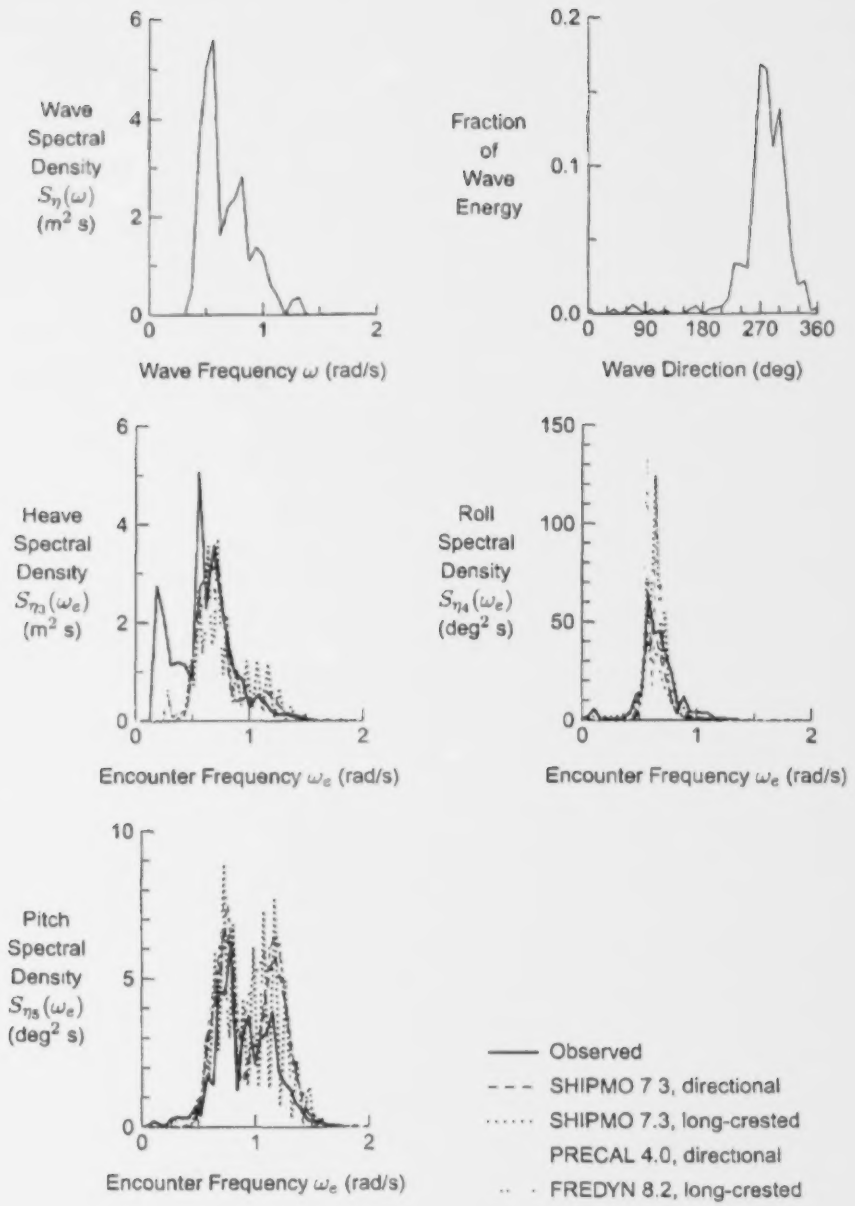
Wave Spectral Density $S_\eta(\omega)$ (m^2 s)
Wave Frequency ω (rad/s)
Fraction of Wave Energy
Wave Direction (deg)
Heave Spectral Density $S_{\eta_3}(\omega_e)$ (m^2 s)
Encounter Frequency ω_e (rad/s)
Roll Spectral Density $S_{\eta_4}(\omega_e)$ (deg^2 s)
Encounter Frequency ω_e (rad/s)
Pitch Spectral Density $S_{\eta_5}(\omega_e)$ (deg^2 s)
Encounter Frequency ω_e (rad/s)
Observed
SHIPMO 7 3, directional
SHIPMO 7.3, long-crested
PRECAL 4.0, directional
FREDYN 8.2, long-crested

Figure 16: *Wave and Motion Spectra for Run 309, 14 knots, Bow Quartering Seas*

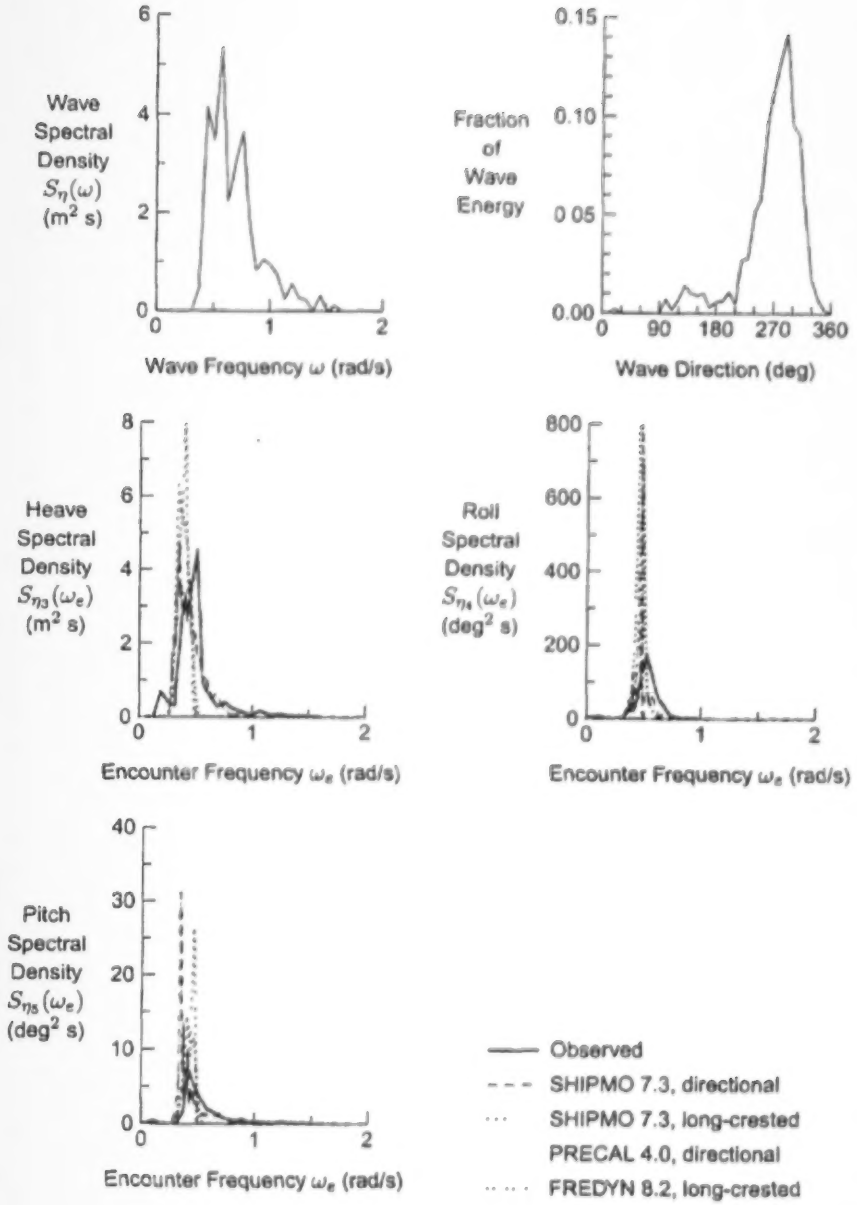
Wave Spectral Density $S_\eta(\omega)$ (m² s)
Wave Frequency ω (rad/s)
Fraction of Wave Energy
Wave Direction (deg)
Heave Spectral Density $S_{\eta_3}(\omega_e)$ (m² s)
Encounter Frequency ω_e (rad/s)
Roll Spectral Density $S_{\eta_4}(\omega_e)$ (deg² s)
Encounter Frequency ω_e (rad/s)
Pitch Spectral Density $S_{\eta_5}(\omega_e)$ (deg² s)
Encounter Frequency ω_e (rad/s)
Observed
SHIPMO 7.3, directional
SHIPMO 7.3, long-crested
PRECAL 4.0, directional
FREDYN 8.2, long-crested

***Figure 17:** Wave and Motion Spectra for Run 310, 14 knots, Stern Quartering Seas*

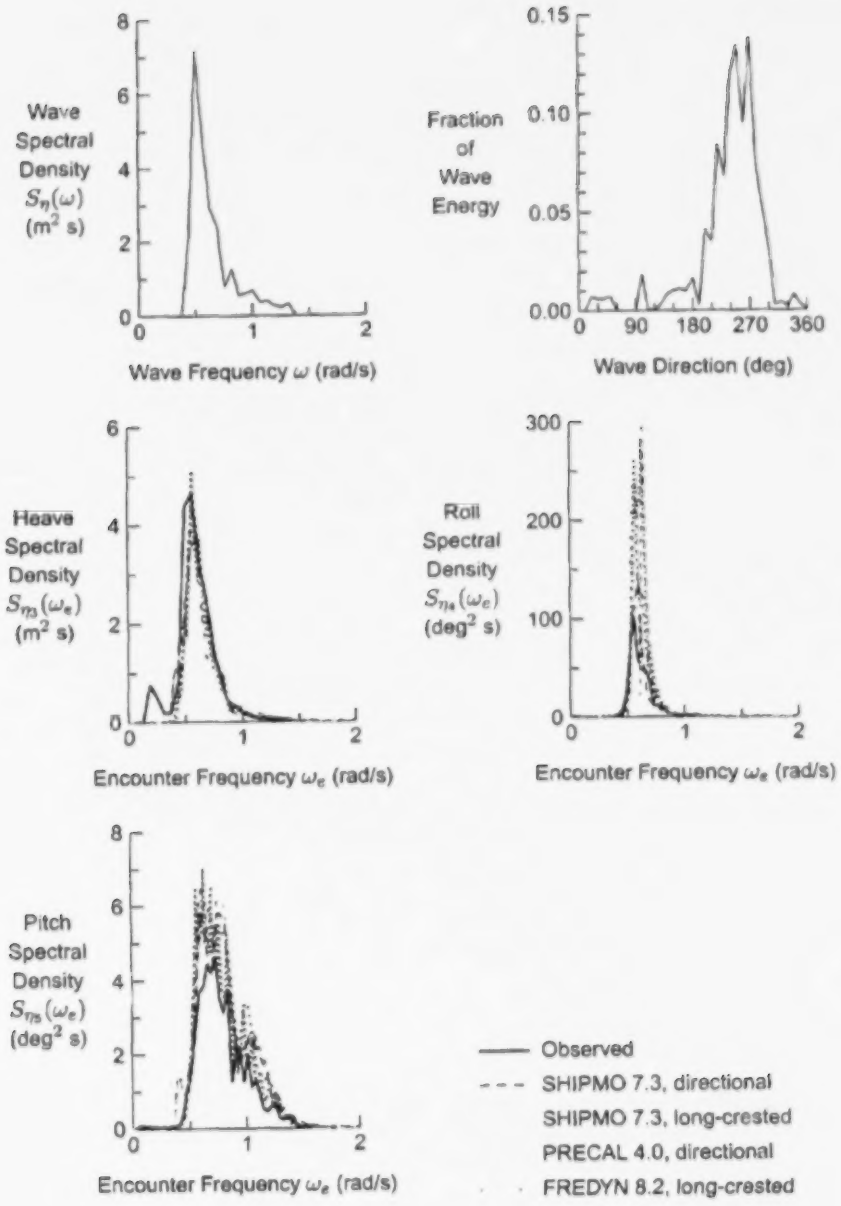
Wave Spectral Density $S_\eta(\omega)$ (m^2 s)
Wave Frequency ω (rad/s)
Fraction of Wave Energy
Wave Direction (deg)
Heave Spectral Density $S_{\eta_3}(\omega_e)$ (m^2 s)
Encounter Frequency ω_e (rad/s)
Roll Spectral Density $S_{\eta_4}(\omega_e)$ (deg^2 s)
Encounter Frequency ω_e (rad/s)
Pitch Spectral Density $S_{\eta_5}(\omega_e)$ (deg^2 s)
Encounter Frequency ω_e (rad/s)
Observed
SHIPMO 7.3, directional
SHIPMO 7.3, long-crested
PRECAL 4.0, directional
FREDYN 8.2, long-crested

Figure 18: *Wave and Motion Spectra for Run 403, 8 knots, Bow Quartering Seas*

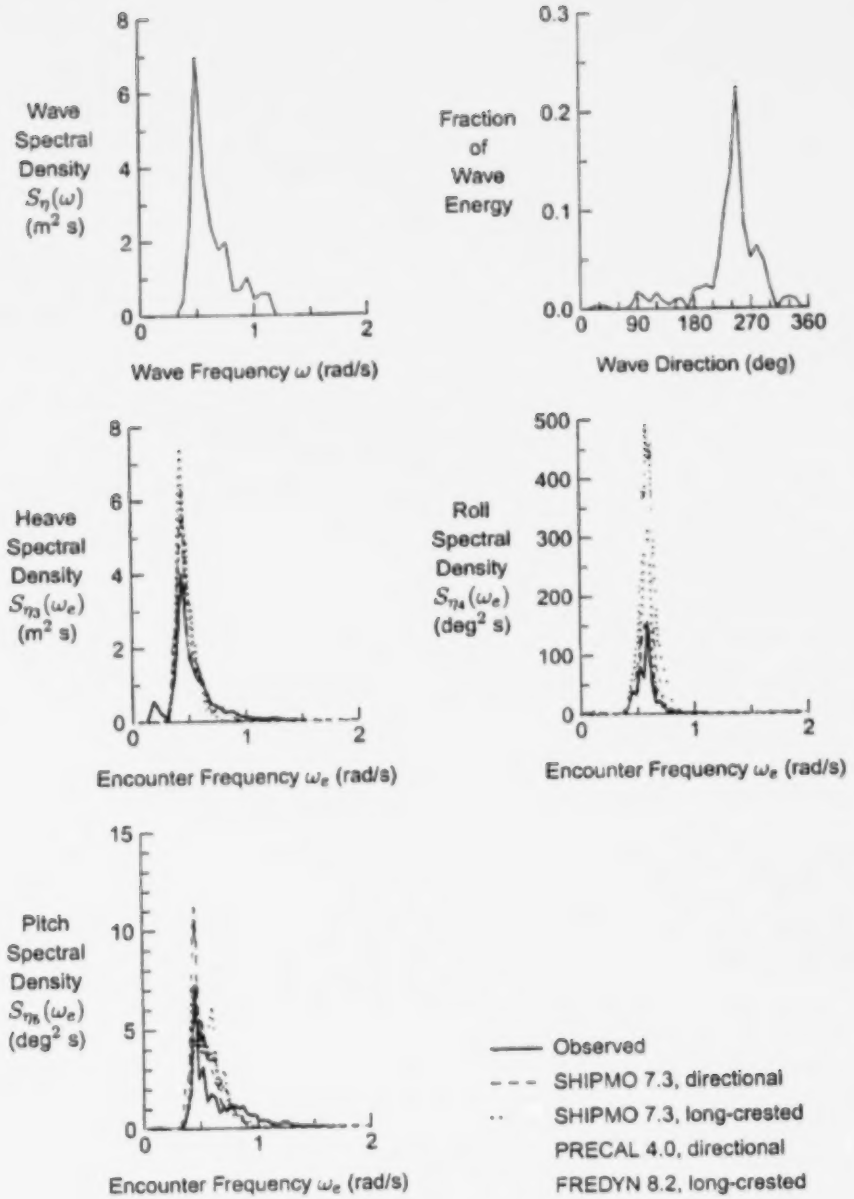
Wave Spectral Density $S_\eta(\omega)$ (m^2 s)
Wave Frequency ω (rad/s)
Fraction of Wave Energy
Wave Direction (deg)
Heave Spectral Density $S_{\eta 3}(\omega_e)$ (m^2 s)
Encounter Frequency ω_e (rad/s)
Roll Spectral Density $S_{\eta 4}(\omega_e)$ (deg^2 s)
Encounter Frequency ω_e (rad/s)
Pitch Spectral Density $S_{\eta 5}(\omega_e)$ (deg^2 s)
Encounter Frequency ω_e (rad/s)
Observed
SHIPMO 7.3, directional
SHIPMO 7.3, long-crested
PRECAL 4.0, directional
FREDYN 8.2, long-crested

Figure 19: *Wave and Motion Spectra for Run 404, 8 knots, Stern Quartering Seas*

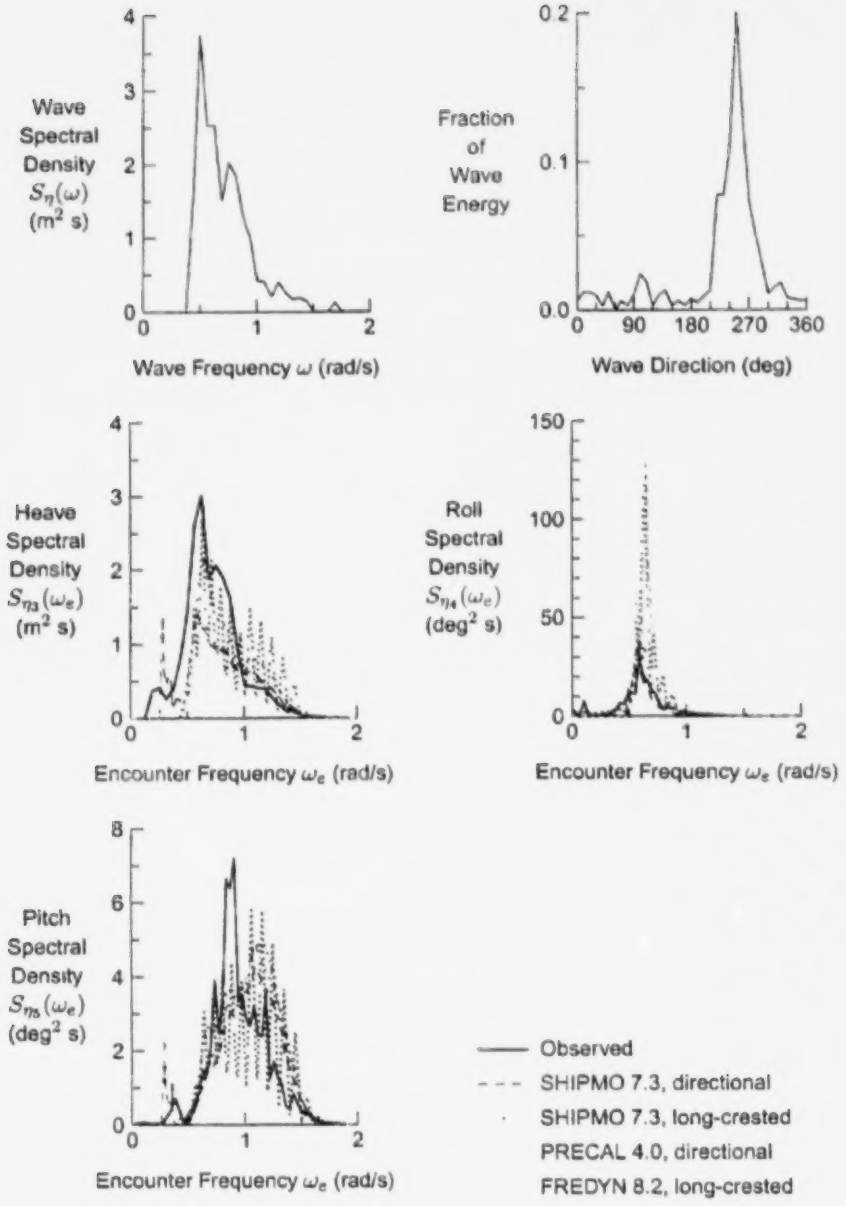
Wave Spectral Density $S_\eta(\omega)$ (m^2 s)
Wave Frequency ω (rad/s)
Fraction of Wave Energy
Wave Direction (deg)
Heave Spectral Density $S_{\eta 3}(\omega_e)$ (m^2 s)
Encounter Frequency ω_e (rad/s)
Roll Spectral Density $S_{\eta 4}(\omega_e)$ (deg^2 s)
Encounter Frequency ω_e (rad/s)
Pitch Spectral Density $S_{\eta 5}(\omega_e)$ (deg^2 s)
Encounter Frequency ω_e (rad/s)
Observed
SHIPMO 7.3, directional
SHIPMO 7.3, long-crested
PRECAL 4.0, directional
FREDYN 8.2, long-crested

Figure 20: *Wave and Motion Spectra for Run 409, 16 knots, Bow Quartering Seas*

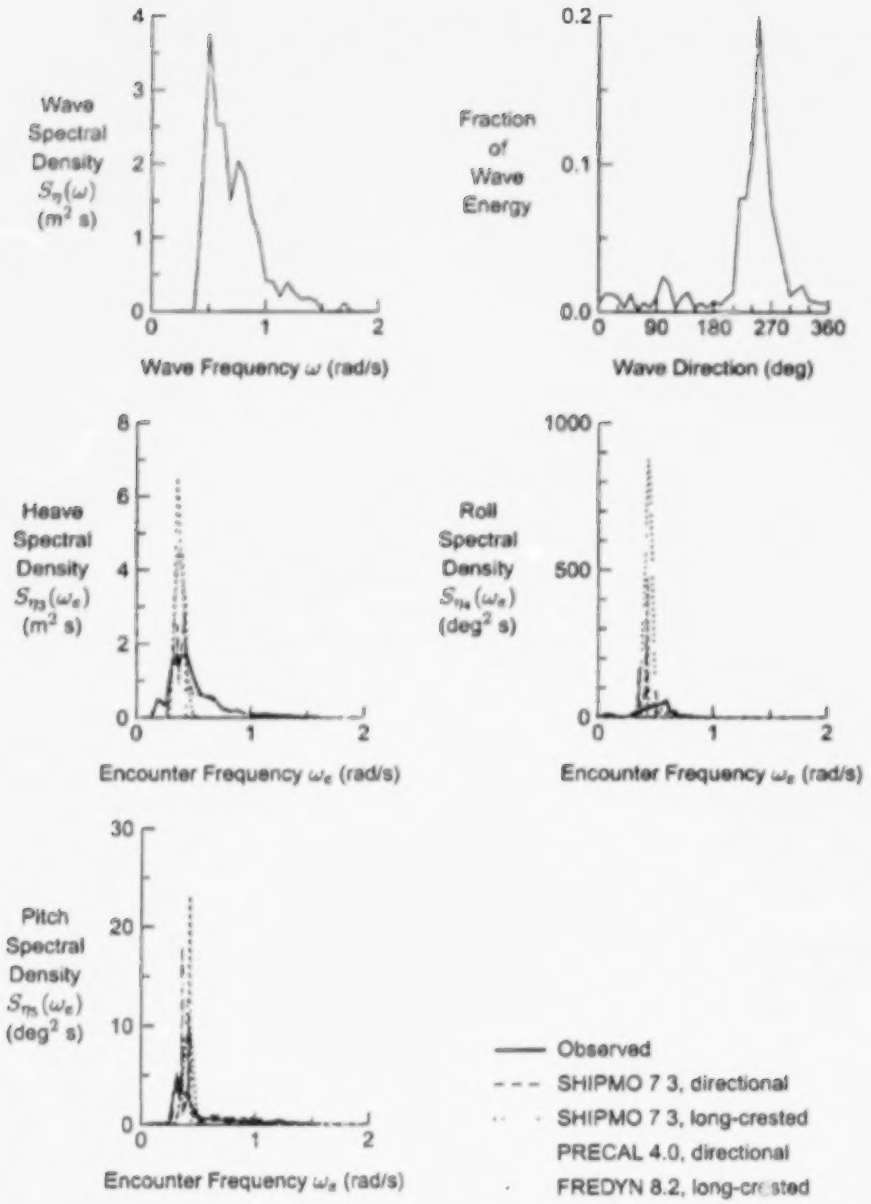
Wave Spectral Density $S_\eta(\omega)$ (m^2 s)
Wave Frequency ω (rad/s)
Fraction of Wave Energy
Wave Direction (deg)
Heave Spectral Density $S_{\eta 3}(\omega_e)$ (m^2 s)
Encounter Frequency ω_e (rad/s)
Roll Spectral Density $S_{\eta 4}(\omega_e)$ (deg^2 s)
Encounter Frequency ω_e (rad/s)
Pitch Spectral Density $S_{\eta 5}(\omega_e)$ (deg^2 s)
Encounter Frequency ω_e (rad/s)
Observed
SHIPMO 7 3, directional
SHIPMO 7 3, long-crested
PRECAL 4.0, directional
FREDYN 8.2, long-crested

Figure 21: *Wave and Motion Spectra for Run 410, 16 knots, Stern Quartering Seas*

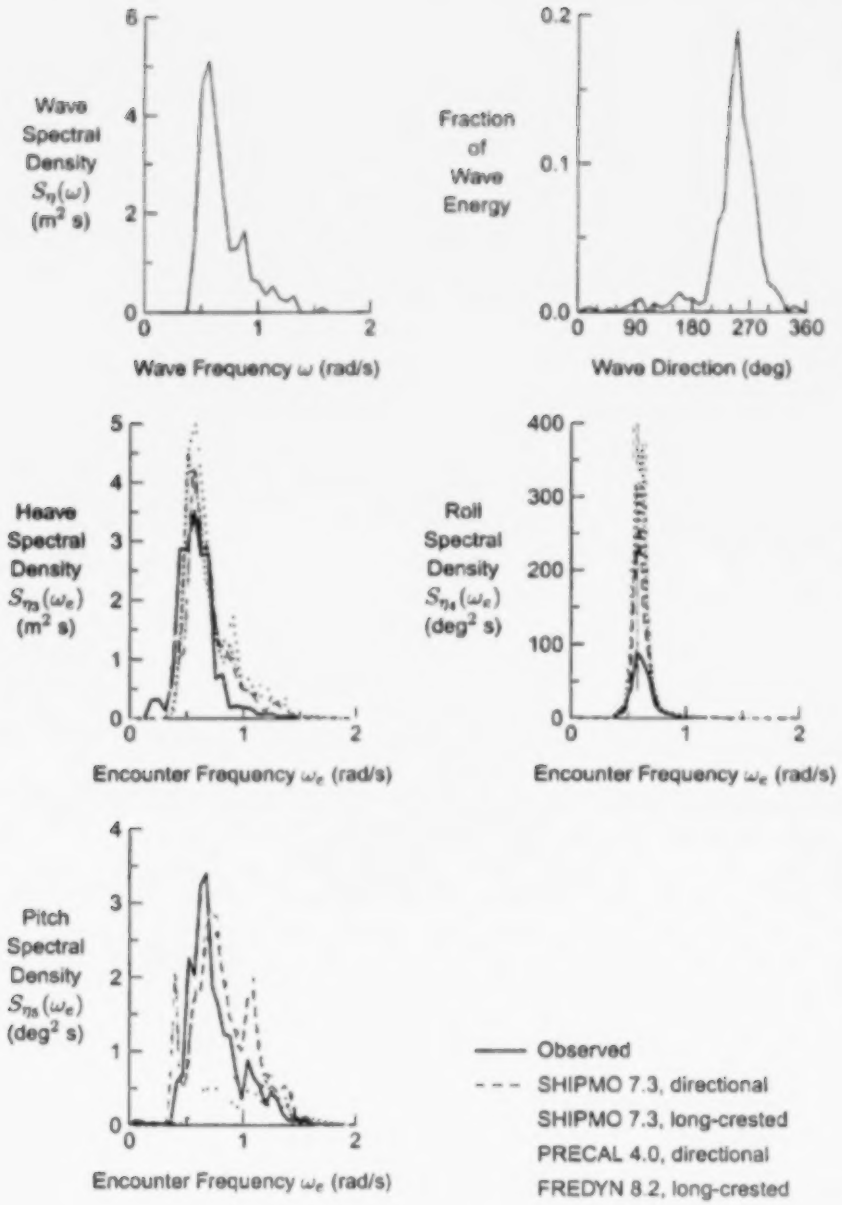
Wave Spectral Density $S_\eta(\omega)$ (m^2 s)
Wave Frequency ω (rad/s)
Fraction of Wave Energy
Wave Direction (deg)
Heave Spectral Density $S_{\eta_3}(\omega_e)$ (m^2 s)
Encounter Frequency ω_e (rad/s)
Roll Spectral Density $S_{\eta_4}(\omega_e)$ (deg^2 s)
Encounter Frequency ω_e (rad/s)
Pitch Spectral Density $S_{\eta_5}(\omega_e)$ (deg^2 s)
Encounter Frequency ω_e (rad/s)
Observed
SHIPMO 7.3, directional
SHIPMO 7.3, long-crested
PRECAL 4.0, directional
FREDYN 8.2, long-crested

***Figure 22:** Wave and Motion Spectra for Run 413, 8 knots, Beam Quartering Seas*

6 Discussion of Results

The motion summaries presented in Tables 3 to 8 are the main focus for the present discussion. The directional predictions from SHIPMO7 give good agreement with the observed motions; thus, the statistics corrected for directional effects at the bottom of Tables 3 to 8 provide a valid basis for comparing all programs.

All programs give good agreement with observations for heave and pitch. Predictions of pitch zero-crossing period are an average of 10 percent greater than observed values. A possible cause for this discrepancy is that pitch gyradius was over-estimated for NIPIGON. Another possible cause is that strip theory tends to overpredict pitch added mass; however, this effect does not explain overprediction by PRECAL of pitch zero-crossing period.

The excellent agreement between observed and predicted zero-crossing periods for roll indicate that the predicted roll natural period for NIPIGON was correct. The RMS roll results suggest that SHIPMO7 is the only one of the 3 programs that provides consistently good roll predictions. PRECAL severely overpredicts roll motion because of the absence of bilge keel damping forces. The performance of FREDYN is also somewhat disappointing, with RMS roll corrected for directional effects being overpredicted by an average of 54 percent. The motion spectra given in Figures 7 to 22 provide additional insight. The great variability of the roll spectral peaks indicates that the variability in roll motion predictions is due to variation of roll damping predictions.

Before discovering that RESCAL does not include bilge keel damping forces, it was thought that the poor roll motion predictions for NIPIGON might have been due to an incorrect input file. The RESCAL input file for NIPIGON was compared with sample input files on the PRECAL 4.0 distribution compact disc, and was consistent with them. One disappointing aspect of the sample PRECAL input files was that they all specified input roll damping values rather than have RESCAL compute roll damping based on geometry; thus, the sample files do not demonstrate the ability of RESCAL to predict roll damping based on input geometry. It is recommended that future PRECAL distributions include sample files with roll damping computed by RESCAL.

The excellent predictions by SHIPMO7 are due in part because the ship geometry and trial conditions are consistent with assumptions of strip theory. NIPIGON has a slender geometry, with an L/B ratio of 8.5 and a narrow stern. The highest Froude number during the trials reported here was 0.25, and the highest significant wave height was 5.82 m.

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7 Conclusions

The programs SHIPMO7, PRECAL, and FREDYN give very good predictions of heave and pitch for the trials with HMCS NIPIGON. The three programs also give very good predictions of zero-crossing roll periods in waves. For RMS roll motions, SHIPMO7 gives very good predictions while predictions from PRECAL and FREDYN are less accurate. With corrections for directional effects, FREDYN overpredicts roll by an average of 54 percent and PRECAL overpredicts roll by a factor of 3. The large overprediction by PRECAL is most likely due to a code error that neglects roll damping forces from bilge keels.

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References

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Annex A
Sample SHIPMO7 Input for Run 203, Directional Seas

```
NIPIGON roll comparison, July 2001, directional spectrum, Run 203
BRITISH  METRIC  SALT  SPEEDCOR   NOSWELLCOR   MODAMP  OUTASCII <-- Flags
Sm203dir.ppr
NOLOAD   NORAW                                  <-- Additional flags
0.2 2.0 0.05                                    <----- Wave frequencies (rad/s)
NOSAVEHY   BOUND2D   LATLONG  HVCOR  <------ Hydrodynamic options
0.1 5.8 0.2                                    <----- Encounter frequencies
INPUTDIR                 <------ Wave spectrum
1                       <------ Number of seaways
C:\Kevin\Nipigon\NWSCRoll\Spectra\R203.spd
1 8.0  <------ Ship speed
356.0 16.67 89.0           <------ Ship length, RG, pitch gyradius
GMCOMP  WETROLLNF          <------ GM, roll natural frequency in water
0.5843          <------ Roll natural frequency (rad/s)
OFFSETS                      <------ Hull definition flag
21 20 1.0 1.0              <------ Number of stations, scaling factors
 1.0
 12
  0.0  0.46  1.19  1.82  2.33  2.57  2.84  3.50  4.50  6.55  9.25 12.79
  0.0  0.00  2.77  6.60  9.93 11.21 12.61 15.53 18.84 23.84 28.78 34.01
 2.0
 12
  0.0  0.49  1.60  2.76  3.61  4.49  5.04  6.56  8.32 11.19 13.65 15.57
  0.0  0.00  1.44  3.62  5.96  8.70 10.56 15.05 19.40 25.42 29.81 32.65
 3
 12
  0.0  0.49  3.07  4.55  5.77  6.90  8.24  9.58 11.19 13.40 15.19 17.16
  0.0  0.00  2.01  3.69  6.06  8.49 11.76 14.97 18.87 23.68 27.30 31.40
 4
 12
  0.0  0.49  3.79  6.43  8.75 10.19 11.53 12.72 14.00 15.38 16.92 18.09
  0.0  0.00  1.54  3.86  7.13  9.97 12.77 15.58 18.86 22.32 26.88 30.34
 5
 12
  0.0  0.55  4.59  8.68 11.01 12.75 14.52 16.01 16.37 17.33 17.92 18.93
  0.0  0.00  1.30  4.19  6.86  9.76 13.47 17.34 18.82 22.12 25.01 29.30
 6
12
  0.0  0.52  7.18 11.60 14.70 15.80 16.62 17.90 18.25 18.81 19.24 19.65
  0.0  0.00  1.93  4.94  8.78 10.59 12.55 16.66 18.65 21.67 25.21 28.14
 7
12
  0.0  0.52  8.78 12.59 15.29 17.10 18.14 19.11 19.64 20.06 20.22 20.27
```

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```
  0.0  0.00  2.10  4.01  6.39  9.04 11.22 14.52 18.60 23.83 26.69 27.53
 8
12
  0.0  0.49  8.87 13.40 16.23 18.61 19.71 20.40 20.47 20.65 20.66 20.74
  0.0  0.00  1.91  3.46  5.27  8.46 11.66 15.12 18.49 22.64 25.47 27.16
 9
12
  0.0  0.49  8.90 14.66 17.43 19.36 20.39 20.84 20.99 20.94 20.92 20.94
  0.0  0.00  1.91  3.49  5.16  7.53 10.58 13.75 19.04 22.18 24.92 27.04
10
12
  0.0  0.46 12.67 16.51 18.66 19.73 20.51 20.87 21.00 20.97 20.92 20.94
  0.0  0.00  2.65  4.16  5.98  7.69 10.03 12.98 16.12 20.72 24.06 26.50
11
12
  0.0  0.43 12.67 16.39 18.53 19.54 20.36 20.77 20.97 20.94 20.92 20.94
  0.0  0.00  2.71  4.32  6.16  7.66 10.15 13.01 16.12 20.72 24.06 26.50
12.0
12
  0.0  0.43  9.90 14.33 17.40 18.87 20.08 20.62 20.91 20.91 20.92 20.91
  0.0  0.00  2.14  3.65  5.66  7.28  9.90 12.95 16.12 20.72 24.06 26.5
13
12
  0.0  0.43 11.53 14.72 16.69 18.74 19.68 20.41 20.81 20.85 20.86 20.85
  0.0  0.00  2.99  4.34  5.66  7.90  9.87 12.64 16.12 20.72 24.09 26.50
14
12
  0.0  0.40  9.56 13.95 17.48 18.76 19.68 20.28 20.60 20.76 20.77 20.75
  0.22  0.22  2.82  4.74  7.34  9.05 11.14 13.63 16.12 20.72 24.03 26.50
15
12
  0.0  0.40  8.36 14.56 16.95 18.51 19.39 20.02 20.26 20.48 20.46 20.45
  0.96  0.96  3.40  6.17  7.99 10.14 12.41 14.93 16.15 20.72 24.06 26.5
16
12
  0.0  0.51  8.41 11.21 14.58 16.45 17.89 19.16 19.40 19.68 19.75 19.80
  2.70  2.70  4.93  5.97  7.66  9.26 11.35 15.27 16.08 20.71 24.05 26.5
17
12
  0.00  0.46  7.66 12.55 14.85 16.35 17.02 17.41 18.10 18.60 18.77 18.84
  5.41  5.41  7.06  8.55  9.99 11.56 12.86 13.86 16.08 20.64 24.02 26.5
18
12
  0.0  0.38 10.20 12.26 13.55 14.62 15.38 15.78 16.32 17.00 17.38 17.64
  8.48  8.48 10.06 10.73 11.48 12.42 13.63 14.69 16.10 20.66 24.01 26.5
19
12
  0.0  6.56  8.93 10.22 11.33 11.97 12.61 13.25 13.82 14.88 15.59 16.10
 10.66 10.75 10.89 11.37 12.02 12.65 13.59 14.83 16.08 20.65 24.00 26.5
20
12
```

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```
  0.0  4.74  6.25  7.23  8.15  8.80  9.65 10.17 10.78 12.20 13.29 14.13
 10.66 10.81 10.97 11.32 11.85 12.45 13.63 14.75 16.06 20.63 24.02 26.5
DRAFT                                <----- Control flag for load waterline
13.927 1.627                    <----- Displacement (LT), LCGFP (ft)
0  20.0 .01                  <----- Seakeeping position data
1                                    <----- Number of bilge keel pairs
10 14               <----- First and last stations spanned by bilge keel
9.82  10.5  18.96  7.010  2.00     <----- Bilge keel data
10.5  11.5  18.780 6.100 2.000
11.5  12.5  18.470 6.000 2.000
12.5  13.5  18.250 6.380 2.000
13.5  14.73 18.210 7.130 2.000
17.87 3.900 60.000              <----- Skeg data
19.16  6.500  5.850 9.920 7.5 6.017  0.0 1       <--- Rudder data
0.000 0.000 0.000 0.000 0.000 0.000 0.000    <--- Rudder roll gains
0.000 0.000 0.000                 <--- Rudder yaw gains
2                       <----- Number of stationary fin pairs
19.30 10.200 10.500 7.400 2.625 2.625 0.000 -101.0 1.000 <--- Outboard arm
19.30 3.800 9.700 7.350 2.625 2.625 0.000 -65.0 1.000   <--- Inboard arm
NOSTAB                               <----- Stabilizer control
```

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Annex B
Sample RESCAL Input for Run 203, Long-Crested Seas

```
PRECAL4 RUN
NIPIGON
MONOHULL
OPTION
OAMD
OMOT
OVIS
OFIN
ENDOPT
ROLLIN
DAMP 0.0
ENDROL
#
#  Regular Wave Responses to define waves with arbitrary height.
#  Note: these records can only be input if no RANWAV records are specified!
#
#REGWAV
#NW      NSS
#WAVEH   H(1), H(2), H(3), ...H(NSS)
#ENDREG
#
#  Random Wave Responses
#  Note: these records can only be input if no REGWAV records are specified!
#
#Run     Hs       Tz
#203     3.73    7.73
#
RANWAV
SHORT
T12     2
NW      1
WAVEP   7.73
WAVEH   3.73
ENDSHO
ENDRAN
#  Fin and bilge keel information
#
# ICON  = 2   Bigle keel + aft pair of fins
#             (Shipmo models inner and outer A-bracked, use average
#             location, double chord to account for the two fins)
FINBLG
ICON      2
#
```

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```
# Fin information
#           span(m),chord(m),thick(m),root submergence(m),bilge radius(m),
#           depression angle(deg), dist centre of press from root(m),
#           x from midships(m), lateral offset from C/L(m),
#           vert position from the WL(m) (negative value),
#           limit of angle of attack (deg)
#FIN1        span, chord, thick, subf, brad, gamf, roota, x, y, z, melima
FIN1    2.25  1.60   0.15   1.42  3.5   83.0  1.13  -50.5  2.13 -1.42 10.0
#Bilge keel information
#BILG        span (m), chord (m), depression angle (deg)
BILG        0.61      20.0       50.0
#BLG1        Y-coord of bilge from C/L of vessel (m),
#           z-coord of bilge keel from the waterline (m)
BLG1        5.65        -2.35
ENDFIN
#
# Rudder Data
#
RUDDER
NRUD 2
#       span(m), chord(m),thickness (m), root submergence (m)
GEOM    3.02      2.06      0.40         1.48
#       X-from midships(m) (+ve fwd),y-from C/L(m) (+ve port),
#       vertical(m) (+ve upwards WL)
POSN    -49.7  1.98 -2.7
#       Bilge radius at rudder location (m)
BRAD    3.5
#       Rudder depression angle (deg)
GAMR    90.000
#       distance between rudder centre of pressure and rudder root (m)
CENP    1.46
ENDRUD
ENDFIL
```

Annex C
Sample FREDYN Input for Run 203, Long-Crested Seas

```
COMMENT   NIPIGON FREDYN input file for seakeeping trial comparison
COMMENT   Prepared by Kevin McTaggart, DREA, July 2001
COMMENT   Autopilot coefficients from MX frigate example.
SIMTIME   3600.0
INITPOS   0.0       0.        0.        0.        0.        133.090   133.090
INITVEL   4.120     0.        0.        0.        0.        0.
RPMPROP   70.612    70.612    70.612    70.612
DEL0      0.        0.
MAN       0         0
DELG0     0.        0.
PSI1M
DELDC     9.0       9.0
C0D
C1D       -3.81     -3.81
C2D       -8.5      -8.5
C3D
C4D
A1D       1.        1.
A2D       0.006     0.006
DEADBAND  1.0       1.0
DELM      35.       35.
RUDAMPL
RUDFREQ
HUMAN
SIMPAR    .001      1         0.        30        0.5
DATFNM    Nipfri.dat
WAVE1     3.719               37        6
WAVESPEC1 0.200     0.000
WAVESPEC1 0.250     0.000
WAVESPEC1 0.300     0.000
WAVESPEC1 0.350     0.000
WAVESPEC1 0.400     0.000
WAVESPEC1 0.450     0.093
WAVESPEC1 0.500     0.551
WAVESPEC1 0.550     2.558
WAVESPEC1 0.600     2.480
WAVESPEC1 0.650     1.846
WAVESPEC1 0.700     1.672
WAVESPEC1 0.750     1.101
WAVESPEC1 0.800     0.776
WAVESPEC1 0.850     0.686
WAVESPEC1 0.900     0.829
WAVESPEC1 0.950     1.074
```

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```
WAVESPEC1 1.000     0.890
WAVESPEC1 1.050     0.618
WAVESPEC1 1.100     0.481
WAVESPEC1 1.150     0.388
WAVESPEC1 1.200     0.248
WAVESPEC1 1.250     0.230
WAVESPEC1 1.300     0.234
WAVESPEC1 1.350     0.179
WAVESPEC1 1.400     0.141
WAVESPEC1 1.450     0.186
WAVESPEC1 1.500     0.026
WAVESPEC1 1.550     0.000
WAVESPEC1 1.600     0.000
WAVESPEC1 1.650     0.000
WAVESPEC1 1.700     0.000
WAVESPEC1 1.750     0.000
WAVESPEC1 1.800     0.000
WAVESPEC1 1.850     0.000
WAVESPEC1 1.900     0.000
WAVESPEC1 1.950     0.000
WAVESPEC1 2.000     0.000
```

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Symbols

A_j	Fourier coefficient
B	ship beam
g	gravitational acceleration
H_s	significant wave height
L	ship length between perpendiculars
$m_{0,i}$, $m_{2,i}$	spectral moments 0 and 2 for mode i
n_t	number of samples in time series
n_{ω_e}	number of encounter frequencies
RPM	revolutions per minute
$S_{\eta_i}(\omega_e)$	motion encounter spectral density
$S(\omega, \beta_s)$	wave directional spectral density
T_z	zero-crossing period
U	ship speed
β_s	relative wave direction
Δt	sample rate
$\Delta\omega_e$	encounter frequency increment
$\delta\omega_e$	smoothing bandwidth
η	motion amplitude
$\eta_i'(\omega, \beta_s)$	motion amplitude in unit amplitude waves
ν	wave component direction
σ_i	RMS motion
χ	ship heading
ω	wave frequency
ω_e	encounter frequency
$\omega_{e,j}$	component encounter frequency
ω_e^*	critical encounter frequency
$\omega_1, \omega_2, \omega_3$	wave frequencies corresponding to encounter frequency

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This report presents comparisons between measured and predicted motions in waves for HMCS NIPIGON. The main objective of the study was to validate roll motion predictions; thus, trial runs selected for the present study are limited to bow quartering, beam, and stern quartering seas. Significant wave heights are between 3 and 6 m, and all wave spectra have a dominant direction. Motion predictions from the time domain code FREDYN and the frequency domain codes SHIPMO7 and PRECAL are presented. FREDYN can only predict motions in long-crested seas; however, the ratio of SHIPMO7 predictions for short and long-crested seas provides a means for estimating motions from FREDYN in short-crested seas. All three programs give good agreement with measured heave and pitch motions. For roll motions, SHIPMO7 gives good agreement while FREDYN gives fair agreement. The poor agreement of PRECAL roll predictions is likely due to the accidental absence of bilge keel damping in Version 4 of the code.

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